NASA SP-5018

TRANSFORMING AND USING SPACE-RESEARCH KNOWLEDGE

(Ten Diversified Views)

NASA-UCLA

SYMPOSIUM AND WORKSHOP

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DEPARTMENT OF DEFENSE
PLASTICS TECHNICAL EVALUATION CENTER
PICATINNY ARSENAL, DOVER, N. J.

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Scientific and Technical Information Division 1964
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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Foreword

"It is our objective," James E. Webb, Administrator of the National Aeronautics and Space Administration, has declared, "to insure that developments resulting from NASA's scientific and technological programs be retrieved and made available to the maximum extent for the nation's industrial and consumer benefit in the shortest possible time, thus strengthening the bridge between technical research and marketable end use."

On June 2, 1964, in accordance with that objective, the National Aeronautics and Space Administration and the University of California, Los Angeles, jointly sponsored a one-day Symposium and Workshop entitled "The Transformation of Knowledge and Its Utilization." This Symposium was the first undertaking of its kind in that geographical region aimed at exploiting the growing reservoir of technology generated by Government-sponsored aerospace research. In order to effect transfer of new knowledge and technology to the non-aerospace economy, engineers, executives, and marketers from potential user industries were invited to learn about these new developments at first hand from qualified representatives of organizations directly engaged in the national space program.

This book comprises a well-diversified selection of papers delivered at the Symposium.

Contents

I. The NASA Program for Technology Utilization

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On March 28, 1963, a conference was held at Dunsmuir House, in Oakland, Calif., treating the subjects Space, Science, and Urban Life. It was a thought-provoking conference at which many capable and reputable persons discoursed on the so-called "reservoir of technology" that remains to be tapped for the solution of urban and national problems. It was considered then, as it is considered now, that the nation's space program represents a significant input to that reservoir—constantly growing—and that the challenge that confronts us is one that asks, "How indeed do we proceed to transform, and thus transfer, our great store of new knowledge and new technology into wider application and increased national and regional benefit?"

The NASA Program for Technology Utilization dates back to 1961, at which time Denver Research Institute was engaged to conduct a survey intended to identify tangible economic non-space by-products of space research, including current applications of past research and future or potential applications of current research. They were also asked to evaluate by-product identification techniques and study the flow of information from space research to commercial applications.

Here is a summary of their findings:

(1) They concluded that the transfer of technology, rather than the transfer of products, has been by far the most important contribution of missile/space programs to the civilian section of the economy. Moreover, it was pointed out that product transfers have not been significant, and that the term "by-product" is misleading, in that it doesn't describe the total transfer process.

(2) The study identified some 33 broad technological areas that have benefited and should continue to benefit.

(3) Emphasis was given to the time lag between space technology and its commercial application, suggesting that most of the transfer is still to occur.

(4) Although the study concluded that transfers from the space program are feasible, the difficulty of tracing the source of contribution—university, industry, or governmental lab, all of which generate new knowledge—is quite complex and probably not worth resolving.

(5) The study pointed out that commercial applications have appeared in almost their original form in the following areas: electronic components and systems, instrumentation, telemetry and communications, and packaging.

(6) Other types of contributions were noted as follows:

- (a) Stimulation of both basic and applied research.
- (b) Development of new or improved processes and techniques.
- (c) Increased availability of materials, along with lab and test equipment.
- (d) Cost reduction.

(7) Mention was made of the gaps that exist between organizations that harbor the new technology and organizations with commercial marketing capabilities. And, finally, the study noted that the communication channels through which technological knowledge flows to secondary uses are not understood, but that informal channels might well exceed in importance the formal channels.

In 1961, there was also initiated the first regional experiment in the Technology Utilization Program, and this was with the Midwest Research Institute. The objective was to identify items with potential application at the various NASA centers, disseminate these to the Midwest industrial community, and test industry's response. This program provided a hard look at, and necessary experience in, the complex problem of effecting transfers.

The next development was an organizational structure and procedure to accomplish the identification, evaluation, and dissemination of new technology within NASA—essentially, to spot, value, and broadcast. The mechanics have remained pretty largely unchanged since their inception. Beginning with identification: at each NASA field center or installation, there is a Technology Utilization Officer, whose task it is to ferret out items with transfer potential. These are noted on a so-called Flash Sheet and reported to Headquarters. You might immediately question the qualifications of one man to make identifications among so many disciplines. In some cases, at the larger centers, there is a small staff to accomplish this work. In all cases, the Technology Utilization Officers enlist the assistance of other technical personnel, and there is one current case involving contracted assistance. As for NASA contractors, they are called upon to report innovations to the cognizant Technology Utilization Officer, and this requirement is spelled out in what is called the "Reporting of New Technology Clause." Certifying compliance with this clause is also a responsibility of the Technology Utilization Officer. As you can imagine, there was quite a lot of semantic wheel-spinning in attempting to define "New Technology" or innovation. An operational definition emphasizes utility; to wit, a means of accomplishing a work objective either more effectively than before or for the first time.

The reporting clause also asks the contractor to indicate the apparent uses of his discovery, improvement, or innovation. The benefits are just as likely to accrue to the contractor himself, via the waiver clause. There is an educational and cooperative effort here that is gaining momentum. Originally a trickle, the flow of reporting from contractors now provides nearly half the input of the Technology Utilization Program.

The next step is evaluation, and, for this, NASA employs the services of research organizations. A preliminary evaluation is made by one research institute, and those innovations marked for further attention are examined by one of four other research institutes. These organizations include ITTRI, Battelle, Stanford, Arthur D. Little, and Southwest Research. It is felt that these organizations are more closely in touch with industry's needs than NASA is. Commercially significant innovations are then prepared for publication.

This brings us to the dissemination effort, which utilizes the trade journals, news media, and professional journals. There is coordination of Technology Utilization activities, I'm told, with the Department of Defense, AEC, Small Business Administration, Department of Commerce, and other pertinent government agencies.

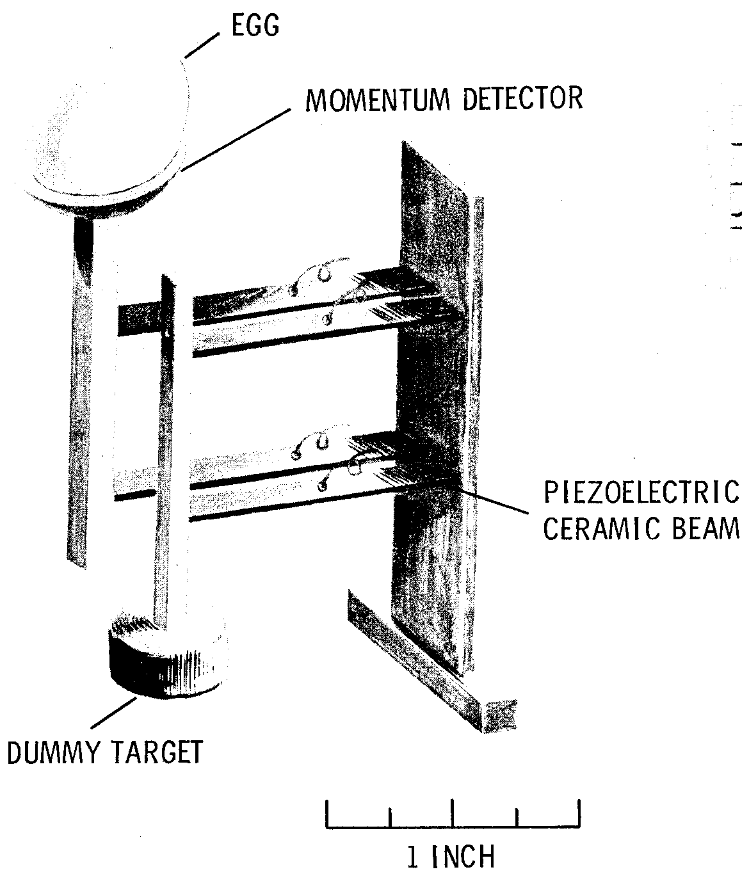
As for publications resulting from the Technology Utilization effort, there is first the Tech Brief. This is a single- or double-page bulletin with a minimum of verbiage, intended to get the information out before it grows old. Approximately 60 of these have been issued to date, and there will soon be double that number. Second is the Technology Utilization Note, which compiles related improvements that belong under a single subject heading, such as "Selected Welding Techniques." Third is the Technology Utilization Report. This represents an extensive evaluation with high industrial potential. These Reports not only stimulate interest, as does a Tech Brief, but answer most of the essential questions. Sample Reports bear titles like "The Retrometer—A Light Beam Communication System," "A Precision Height Gage," and "A Micrometeorite Transducer." Last, we come to the Technology Survey. These represent state-of-the-art surveys that highlight NASA's contribution. One has already been published on "Bearing Technology," and there are several under preparation, on such subjects as "Fuel Cells," "Valve Technology," "Inorganic Coatings," "Microelectronics," "Antennas," "Opti-

cal Fabrication Techniques," "Plasma Jets," and "Magnetic Tape Recorders." The surveys have been undertaken by university personnel, research institutes, and private corporations.

To stimulate industry to take a direct and active interest in the Technology Utilization information, additional regional projects have been initiated—experimental, yet as practical as experience permits. One of them—called ARAC, for Aerospace Research Application Center—began last year at Indiana University. These regional projects receive all the unclassified literature put out by NASA, amounting thus far to some 80,000 report titles, plus an additional 4,000 each month. This pretty well covers the substance of NASA's R&D effort. ARAC's service is to select from this mass of materials that which is pertinent to the 29 companies that constitute its clientele. The technical interests of each company are developed into an "Interest Profile," which then governs the information flow. The entire program has been judged of sufficient promise to warrant additional support this year beyond that provided by the fee-paying clients. At Wayne State University, in Detroit, a Technology Utilization Program has been launched that is funded by regional industries, the State of Michigan, and NASA. A distinguishing feature is the use of graduate industrial engineers. Another program is being organized at the University of Pittsburgh, making maximum use of computers for search and retrieval. Regional industry there is also participating in the funding.

What have we found? Here are some samples:

Figure I–1 reveals a device developed at the Ames Research Center to measure micrometeorite impacts on spacecraft. Vernon Rogallo took a pair of piezoelectric beams and formed



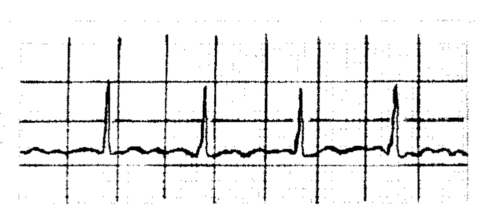


FIGURE I–1.—Former micrometeorite detector shows promise for drug research.

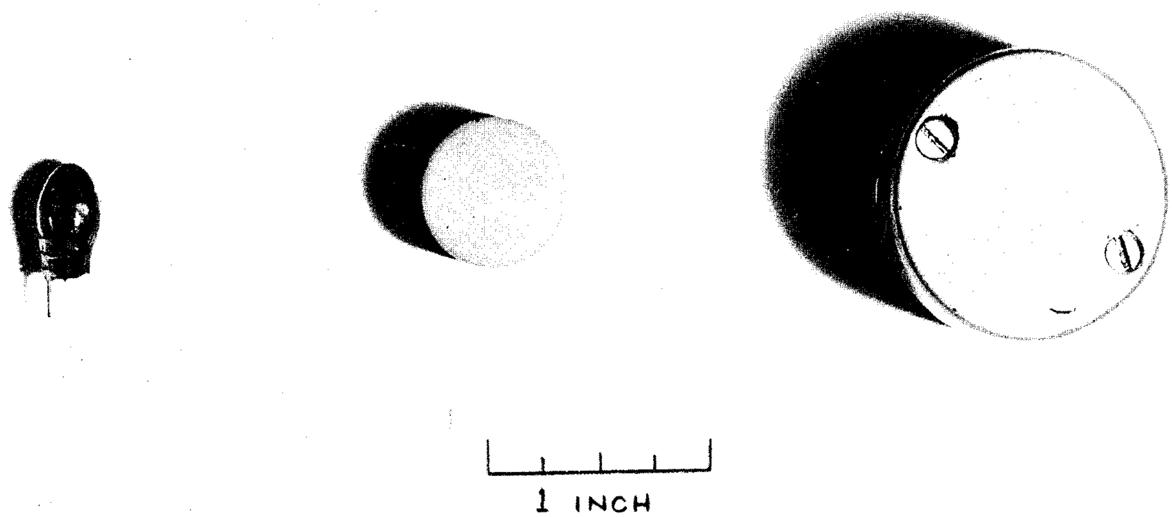


FIGURE I-2.—Three telemeters evolve into medical instruments.

them into a spring-mass system, so that the target mass is suspended by the beams. The instrument is sensitive to forces in the order of a microgram. An impact on the target causes a deflection of the piezoelectric elements, which generate a voltage proportional to the impact momentum. It is an inexpensive device, and in figure I–1 it is shown being used to detect the heartbeat from a bobwhite egg. This suggests utility as a research tool in evaluating drug effects on developing embryos. It has also been used as a laser-beam calibrator and an ion-beam impact sensor.

Figure I–2 shows three telemeters, which followed a logical course of development. The teardrop shape was designed at Ames for ballistic studies, back in 1961. It was converted into a biotelemeter to detect and transmit signals of human heartbeat and respiration. The device in the center, produced by a NASA contractor, is only .20 cubic inch in size, can be pasted to the skin, and will beam signals a distance of 20 feet to a receiver. I'm told that Ames has since increased the range to 100 feet, and further reduced the size of this device. The largest device in the photo is the one we're told will soon be available commercially. It will be used to monitor cardiac and respiratory rates of hospital patients.

In figure I–3 is shown a device that has been given considerable publicity lately. It resulted from efforts to overcome the radio blackout during re-entry. The Langley Research Center came up with this solution—not new, but using a space-age material. It consists of a corner reflector that returns a light beam to its source. Of the three surfaces used in the corner reflector, two are mirrors and the third is a Mylar diaphragm. (Mylar is the material used in the Echo satellites.) The diaphragm vibrates acoustically in response to the human voice. Thus we have a cordless microphone requiring no power other than voice power.

Figure I–4 depicts a contraption designed by Space General Corporation, in El Monte, Calif. It is named Lunar-Tic, and its original purpose

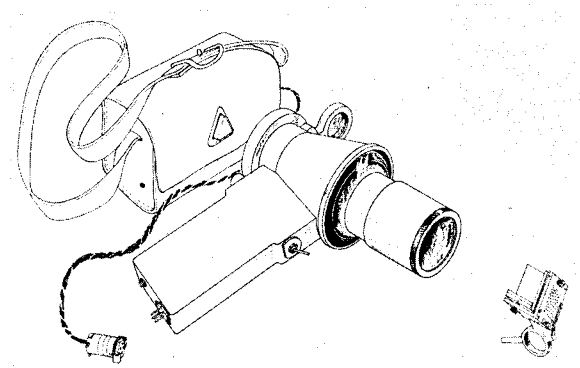


FIGURE I-3.—This cordless microphone emerged from a re-entry problem.

was to make an unmanned exploration of the Moon's surface. It can carry cameras or radio equipment. The program for which it was designed was never funded. However, NASA brought it to the attention of the personnel at Santa Monica's Prosthetics Center, to see if it might be adapted to the use of limbless children. The device weighs about 25 pounds; can go over 6- to 18-inch obstacles, depending on the design of the legs; can climb a 45-degree slope; and uses only a $\frac{1}{70}$-h.p. motor. If the adaption is successful—and a proposal has been submitted to the National Institutes of Health—this device would allow a legless person to negotiate beach sand, open fields, street curbs, and wide stairs. We're told there are approximately one million persons in the United States who might benefit from this device. The hope is that its features, if proved satisfactory, can be combined with an electric wheelchair to provide the advantages of both.

The goal of NASA's Technology Utilization Program is to exploit fully and profit progressively from the space-research opportunities inherent in the new knowledge and technology generated by the entire enterprise of space exploration. We're unsure of the most expeditious method of accomplishing this goal, but we're confident that innovation is just as applicable to methodology as it is to hardware.

It is worthwhile here to emphasize the resource that is represented by some 70,000 engineers and scientists who are supported by the space program. These men should be

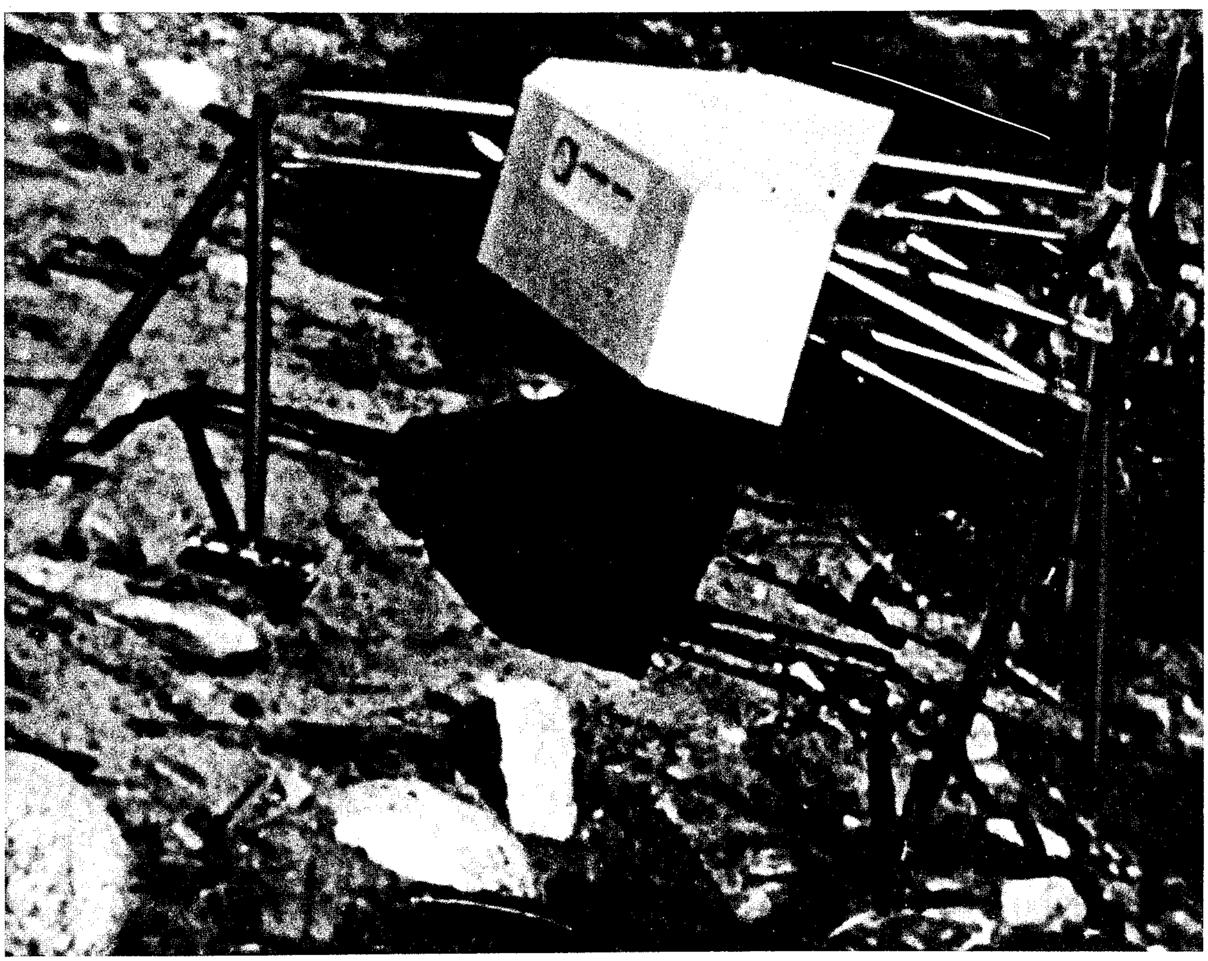


FIGURE I-4.—An intended moon-walker may benefit limbless children.

classified as knowledge generators, and a number of them have unique experience in managing gigantic projects. If we can succeed in interesting them in the problems and promise of application, we shall have initiated the momentum toward a higher order of abundance. Just three weeks ago, Wernher von Braun remarked to a small group of us that he considers the applications effort as the most important activity in which NASA is engaged, not excepting the visit to the Moon. He traced the theory and uses of thermonuclear energy to prove his point.

Recently, President Johnson, speaking at the University of Michigan, alluded to pursuit of the Great Society. "In the next 40 years," the President said, "we must rebuild the entire urban United States."

That will take a lot of doing, but the reason that it needs doing is testimony to the fact that knowledgeable people cannot continue to pursue their own super-sophisticated specialty in the hope that the whole cloth will construct itself. We're anxious to exchange technology; to stimulate a creativity, with space research as the trigger; to match particular needs, of which many are aware, to particular findings, of which many are not.

II. Bonding and Welding of Dissimilar Metals

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Joining dissimilar metals by brazing and welding is a technology that is directly applicable to new products. Significant advances in metal-couple joining technology developed at North American Aviation in support of space programs were needed to meet the complex requirements of many advanced aerospace-material applications that frequently cannot be satisfied by a single metal; instead, a combination of several metals is needed. Furthermore, a sound, strong metallurgical bond between the dissimilar metals is mandatory. Generally, it is required to be as tough and leakproof as the parent couple in order to withstand acoustical and mechanical vibration during launch, thermal cycling, and the rigors of the space environment.

The requirements arise principally because tanks and vessels for both highly corrosive and cryogenic-hazardous propellants, fluids, and gases are made of high-strength aluminum, stainless-steel and titanium alloys. For example, stainless-steel expansion bellows must be joined to aluminum tubing, and titanium vessels and aluminum tubing require stainless-steel valves in their plumbing.

One typical advanced space program that Space and Information Systems Division of North American Aviation has studied requires procedures for joining large-diameter (up to 50 inches) AISI 321 stainless steel to 2219 aluminum-alloy tubing on a production basis. In addition to the metallurgical difficulties besetting this bimetallic union, incompatible thermal coefficients and conductivities must be accounted for. Preliminary R&D effort indicates that brazing and solid-state bonding are both feasible. Figure II–1 shows an eight-inch-diameter brazed joint of 321 stainless steel to 6061 aluminum alloy.

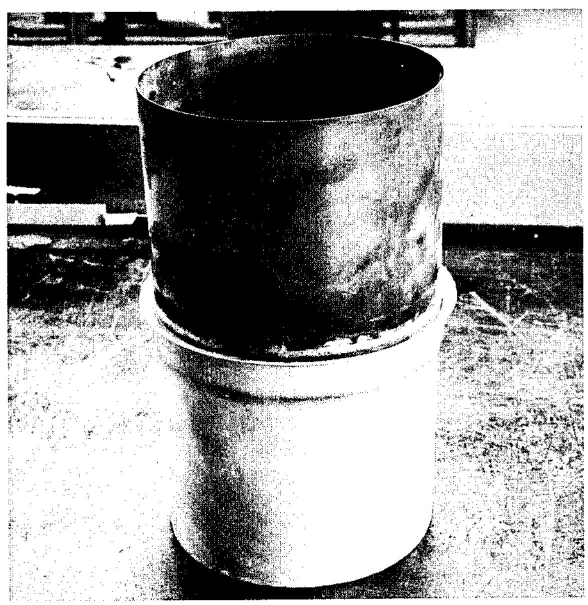

Figure II–1.—Eight-inch-diameter brazed joint of 321 stainless steel to 6061 aluminum alloy.

PROBLEM AREAS

The Engineering Development Laboratory of S&ID, NAA, has been actively engaged in the technology of joining dissimilar metals for the large boosters and space vehicles (ref. 1).

Dissimilar metals can be joined directly by brazing and welding. However, the resultant metallurgical bond is usually exceedingly brittle and shock-sensitive, and exhibits relatively

inferior mechanical properties (ref. 1). Table I indicates the dissimilar-metals bonding processes developed at NAA.

Brittle phases are formed when sufficient interchange of emigrant atoms occurs within a bimetallic couple. This mechanism is present on a macro scale during welding. It is less prominent in brazing, and least effective when solid-state diffusion operates. However, when excessive times, pressures, and temperatures are dominant in the profiles of the latter two operations, joint-brittleness phases may be expected if it is the prevalent mechanical behavior of a solid state whenever large numbers of dissimilar atoms are exchanged by the parent metals.

Brittleness as a mechanical characteristic is not intolerable in designs that can utilize this property to advantage. Brittle ceramics and cermets are examples of materials that are useful in specialized applications. The importance of designing with inherently brittle structural materials is emphasized and recommended by several NASA advisory groups (refs. 2 and 3).

However, brittle materials can be accommodated only when service conditions *do not* require thermal or mechanical impact insensitivity and resistance to vibration.

For example, steel can be joined directly to aluminum, without the aid of an intermediate layer. However, the resultant bond incorporates a brittle phase of aluminum-ferrite (Fe_3Al). When this brittle phase extends into a continuous film or network around the grain structure, the entire joint is subject to a loss of ductility.

In this representative bond, a brittle phase can form in three ways: (1) by alloying of the molten aluminum and molten steel, which occurs in welding; (2) by the solvent action of molten aluminum on steel, which occurs in brazing; and (3) by the transmigration of the aluminum and iron atoms, during diffusion bonding. To prevent the formation of a brittle phase, some intermediate material is needed to act as a barrier to prevent the combination of the aluminum and steel, and to provide a surface to which both materials can bond (ref. 1).

The two methods proven to be the most likely means of obtaining leakproof bonds of

TABLE I.—*NAA Dissimilar-Metal Bonding Processes*

Union	Procedure
Aluminum to stainless steel	Dip-braze after tin-coating the stainless steel.
Aluminum to stainless steel	Soldering after nickel-plating the aluminum.
Aluminum to stainless steel	Diffusion-bonding after interface coating application.
Stainless steel to molybdenum	Vacuum-braze.
Titanium to aluminum	Soldering after nickel-plating Ni on Ti and aluminum.
Copper to nickel	Diffusion-bonding after tin-soldering.
Aluminum to stainless steel	Dip-braze after silver-plating of stainless steel.
Aluminum to beryllium	Direct dip-braze.
Stainless steel to beryllium	Vacuum-braze.
Columbium to molybdenum	Diffusion-bonding honeycomb sandwich.
Columbium to stainless steel	Inert-gas braze.
Tungsten to titanium Tungsten to copper Tungsten to stainless steel Tungsten to aluminum Titanium to aluminum	Tungsten-arc inert-gas brazing with aluminum brazing alloy.
Titanium to stainless steel	Resistance-welding-machine braze.
Tungsten to molybdenum	Electron-beam welding.
Molybdenum to columbium	Electron-beam welding.
Molybdenum to stainless steel	Electron-beam welding.
Nickel wire to copper wire	Capacitor-discharge-resistance microwelder.
Stainless steel to low-alloy steel	Percussion-stud welding.

high strength and toughness, and practical implementation in production of large-diameter tubing, are brazing and diffusion bonding.

BRAZING

Aerospace brazing processes, developed and in use at S&ID, involve the use of several common production techniques. A joint is presently produced by brazing 6061 aluminum alloy to 304L stainless steel. In this method:

(1) The 304L stainless steel is hot-tinned.

(2) The aluminum is cleaned for brazing by the conventional hot-alkaline and mixed-deoxidizer immersion process.

(3) The joint is assembled with aluminum as the external member of the joint. Alcoa 718 alloy filler wire is preplaced in the joint crevice.

(4) The assembly is hot-salt-bath brazed, and subsequently cleaned by conventional methods.

(5) The joint is welded in place. The 304L is welded to 321 stainless steel, and the 6061 aluminum is welded to 6061 aluminum.

The tin on the 304L stainless steel serves as a barrier material even though it is in a molten state at the brazing temperature. Photomicrographs of joints have revealed a continuous layer of tin on the 304L stainless steel. The brazing alloy forms an aluminum-tin alloy layer adjacent to the tin barrier layer. The alloy probably has a maximum content of 5-percent tin, because this is the solubility limit of tin in aluminum. The percent of tin rapidly diminishes with a small increase in distance from the tin layer.

Joints made by this process have been subjected to vibration, cryogenic thermal shock, and pressure burst-testing without any joint failure. Maximum leak rates of 10^{-8} cc of helium/second have been required and attained from all joints. Higher-strength aluminum alloys, such as 2219, can also be brazed to stainless steels. The limiting factor is temperature. Often the melting point of the braze alloy approaches that of the parent aluminum alloy. Figure II–2 shows a series of two-inch-diameter brazed joints of 321 stainless steel to 6061 aluminum after burst test.

A literature survey was conducted to determine candidate alloys for brazing Inconel X. As a result of the survey, the following alloys were selected for testing:

81.5 Au, 16.5 Cu, 2.0 Ni
52.5 Cu, 38.5 Mn, 9.0 Ni
72 Au-22 Ni-6 Cr
82 Au-18 Ni

For testing, a pyrex tube is placed over the joint area, and the ends of the pyrex tube are sealed with specially machined fittings. This forms the inert-gas envelope. An induction coil is placed around the union outside the pyrex tube, and the envelope and the inside of the specimen are purged with argon gas.

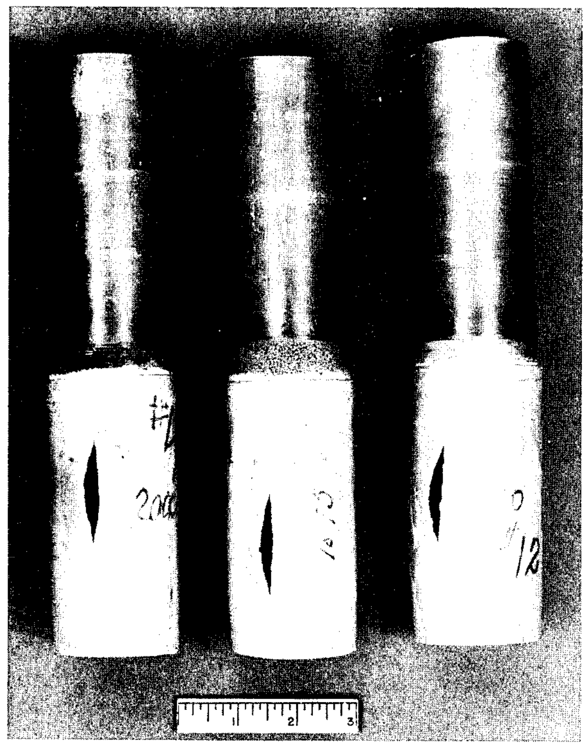

FIGURE II–2.—Two-inch-diameter brazed joints of 321 stainless steel to 6061 aluminum after burst test.

The results of the brazing operations and metallurgical examinations indicated that the 72 Au-22 Ni-6 Cr braze alloy is suitable. Figures II–3 through II–6 indicate the results of specimens after various steps in testing.

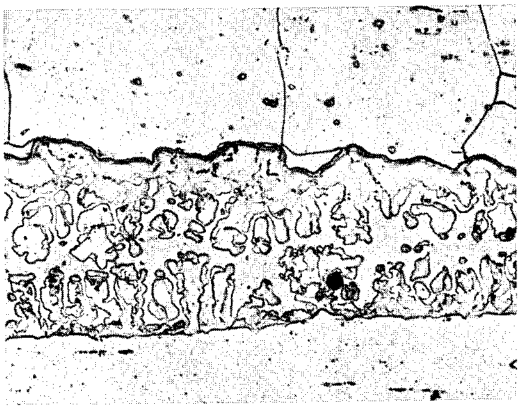

FIGURE II-3.—Inconel-X braze alloy, 304L stainless-steel interface, showing normal joint. ×150.

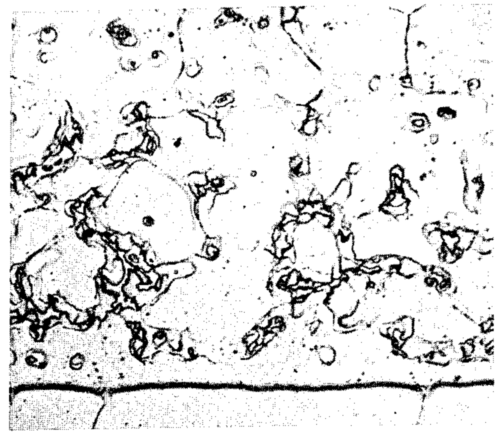

FIGURE II-4.—Inconel-X braze alloy, 304L stainless-steel interface, showing solution of Inconel-X by the braze alloy and extension of grain boundaries. ×150.

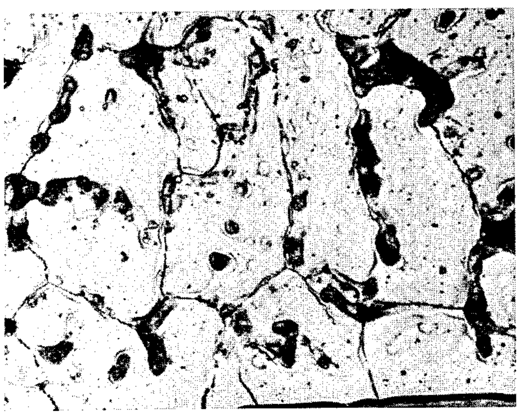

FIGURE II-5.—Inconel-X braze alloy, 304L stainless-steel interface, showing solution of Inconel-X by the braze alloy and extension of grain boundaries. ×150.

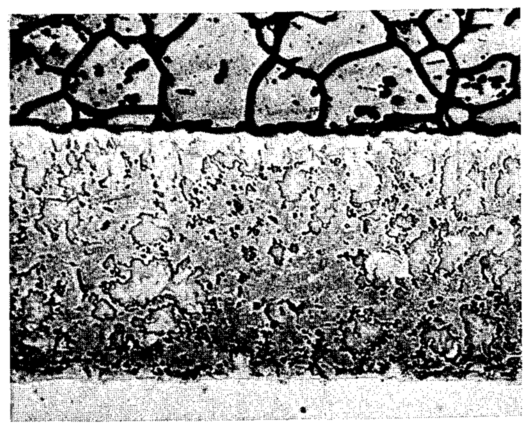

FIGURE II-6.—Inconel-X braze alloy, 304L stainless-steel interface, depicting extensive grain-boundary precipitation due to prolonged brazing cycle. ×150.

Helium leak-rate determinations were made on the joints. All had leak rates less than 2.0×10^{-8} cc of He/sec., the required rate of minimum leak (see table II).

Radiographic inspection was performed on all joints. Irregular-shaped lines appearing on each side of the joint are spongy areas in the braze alloy, caused by the brazing technique. They are not considered detrimental.

DIFFUSION-BONDING

Preliminary studies at S&ID of a diffusion-bonding method for aluminum-to-aluminum joining indicate that the process can be adapted effectively to bond 2219 and other aluminum alloys to 321 stainless steel. The joint is primarily designed to be fabricated as a separate entity, and the metals welded to their counterpart during assembly.

The process, as adapted to joining dissimilar metals, is as follows:

(1) An interface material is applied and bonded to the surface of the stainless steel.

(2) The same interface material is plated onto the aluminum alloy.

(3) The parts are assembled with the aluminum as the external member, and then heated to bonding temperatures. External pressure is applied on both members of the joint during

the bonding cycle, keeping the two surfaces in intimate contact.

The interface material serves two purposes: it is used as a bonding agent and as a barrier material. This is possible because of the time lag involved in diffusion.

During the heating process, two separate bonding mechanisms occur in the joint. There

TABLE II.—*Test Data for Inconel-X Tubing Brazed to 304L Stainless-Steel Braze Alloy—72 Au-22 Ni-6 Cr*

Specimen	Ultimate stress ² (psi)	0.2-percent yield stress (psi)	Burst pressure (psig)	He leak rate⁵ $\times 10^{-8}$	Radiographic inspection
111	(2) 90, 800	37, 500		0	* (6)
112			(8) 6, 100	0	*
113	(2) 90, 800	39, 000		0. 1	*
114	(4)			0	*
115	(2) 90, 400	40, 900		0	*
116	(2) 90, 400	40, 900		0	*
117			(7) 7, 125	0	*
118			(7) 7, 200	0	*
119	(2) 91, 200	39, 500		0	*
120	(4)			0	*
121			(7) 7, 100	0	*
122	(3) 98, 700	45, 900		0	*
123	(3) 100, 300	56, 000		0	*
124			(7) 7, 150	0	*
125	(3) 100, 800	53, 800		0	*
126	(2) 90, 400	39, 200		0	*
127	(4)			0	*
128	(3) 99, 800	54, 500		0	*
129			(8) 6, 100	0	*
130			(8) 6, 100	0	*
131			(7) 7, 250	0	*
132			(8) 6, 050	0	*
133			(8) 6, 050	0	*
	(9) (10) Average	(11) (12) Average	(13) (14) Average		

(1) All tests were conducted at room temperatures.
(2) Tensile-test failures occurring on 304L stainless-steel side.
(3) Tensile-test failures occurring on Inconel-X side.
(4) Samples for metallurgical analysis.
(5) 0=less than 1×10^{-10} std cc. He/sec.
(6) Radiographic inspection indicates joint is generally acceptable.
(7) Rupture occurred on Inconel-X side.
(8) Rupture occurred on 304L Cres side.
(9) 304L stainless steel—90,660 psi.
(10) Inconel-X—99,900 psi.
(11) 304L—39,500 psi.
(12) Inconel-X—52,050 psi.
(13) 304L—6,080 psi.
(14) Inconel-X—7,185 psi.

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is a substitutional diffusion process between the interface material and the steel. The migration of atoms between the two materials is an attempt to equalize the concentration differences, and produces a bond that is theoretically at least as strong as the parent material.

Bonding of the interface material to itself also occurs. When the two surfaces are held in intimate contact, so that they are at a distance of two atomic diameters apart, a bond will form that is similar to the cohesive forces bonding the atomic-lattice submicrostructure of the interface material. Bonding parameters of significance are: (1) the concentration of interface material that will produce the strongest joint, (2) the time and temperature profile that will produce the strongest joint, and (3) the formation of brittle phases.

COLD PLATES AND HEAT EXCHANGERS

Absorption and transportation of heat generated by electronic gear in spacecraft is accomplished by flat, compact cold plates. The heated solutions within the cold plates are then circulated to external radiators, where they are cooled and returned to the interior. This continued cycle requires precise passageways for the solution and extraordinarily fine tolerances over relatively large plane surfaces. The diffusion bonding process is employed at S&ID to produce cold plates and space radiators (ref. 1).

In addition to the factors mentioned above, a supplemental process was required. These parameters were:

(1) Pressure requirements to achieve compression at the bonding temperature.

(2) The correct bonding temperature.

(3) Development of operational procedures to eliminate face-sheet depression over lightening cavities.

(4) The development of plating parameters for the interface material.

Cold plates are presently being produced by diffusion-bonding 5052 aluminum to 6061 core plates, with silver as the interface material. Diffusion-bonding of alclad aluminum alloys will also be employed to fabricate space radiators and other components for the environmental-control system of space vehicles.

Experiments have also shown that 2024 to 2024, 7075 to 7075, and 6061 to 6061 aluminum alloys can be joined by diffusion-bonding, with copper as the interface material. Pressure on the joints is applied by steel clamps. The clamped assembly is heated to the bonding temperature in an argon-gas atmosphere. The greater rate of expansion of the aluminum against the lesser-expanding steel provides the bonding pressure.

Cold-plate testing.—An X-ray microprobe study of cold-plate diffusion-bonded joints was performed with two specimens, representing satisfactory and unsatisfactory bonding. The qualitative conditions for good and poor bond structures were previously established by pressure-testing of processed cold plates and by subsequent metallographic analysis.

During the study, pressure-cycling tests were conducted to obtain data on the structural integrity versus test pressure on cold plates (ref. 8). The cold-plate test specimens were subjected to 5000 cycles of pressure at 0 to 150 psi, 2250 cycles at 350 to 500 psi, and 450 cycles at 50 to 500 psi (all cumulatively) without failure. The test specimens were cold plates with .020-inch skins exposed to test pressures of 500 to 1150 psi. Although several specimens bulged when subjected to the higher pressures, the deformations indicated yielding of the face sheets without rupture of the bond interface.

DISSIMILAR-TUBE JOINING

A requirement for joining Inconel X nickel-base-alloy tubing to 304L stainless-steel tubing for a space gas-storage system initiated a study of joining 304L stainless steel to Inconel X by automatic TIG welding and induction-brazing. The study established process parameters and selected a suitable brazing alloy necessary to produce joints meeting the design requirements (ref. 9).

The standing edge for welding was made by flanging the tube end and machining to given dimensions. The specimens were automatically TIG-welded with a flange height of .030 inch and a width of .020 inch. Visual examination of these specimens indicated uniform penetration and an average reinforcement of

.010 inch on the root side of the welds and no undercutting or lack of fill (ref. 9).

Metallographic examination of the weld-fusion zone indicated an acceptable structure. A precipitation of constituents into the grain boundaries on the Inconel side of the joint occurred. However, this condition has no effect on the ultimate strength.

The welded-tube specimens were subjected to axial-tension tests, burst tests, radiographic inspection, and the helium leak rates were determined. Axial-tension tests indicated an average tensile strength of 88,000 psi ultimate, 42,600 psi yield strength, with failure occurring in the weld-fusion zone of the 304L stainless-steel member. Burst-test failures occurred in the 304L stainless-steel tube outside of the heat-affected zone (see fig. II–7) at an average pressure of 6,315 psi. Helium leak rates were less than 1.0×10^{-8} Std cc He/sec when tested by mass spectrometer (ref. 9).

RESISTANCE-WELDING

Stored-energy welding is the resistance-welding method in which weld energy is released from a capacitor bank instead of directly from a power line. The principle of separating the actual welding cycle into a charging phase and a discharging phase allows the energy to be discharged in only a few thousandths of a second, concentrating the heat at the interface of the workpieces. The result is the most efficient use of weld energy known. Most popular applications for this technique are found where welds must be made adjacent to sensitive semiconductor materials or glass seals, with spring materials, and highly conductive or dissimilar metals (ref. 4). S&ID employs resistance-welding for miniature, high-density electronic modules. Figures II–8 and II–9 show examples of resistance welding.

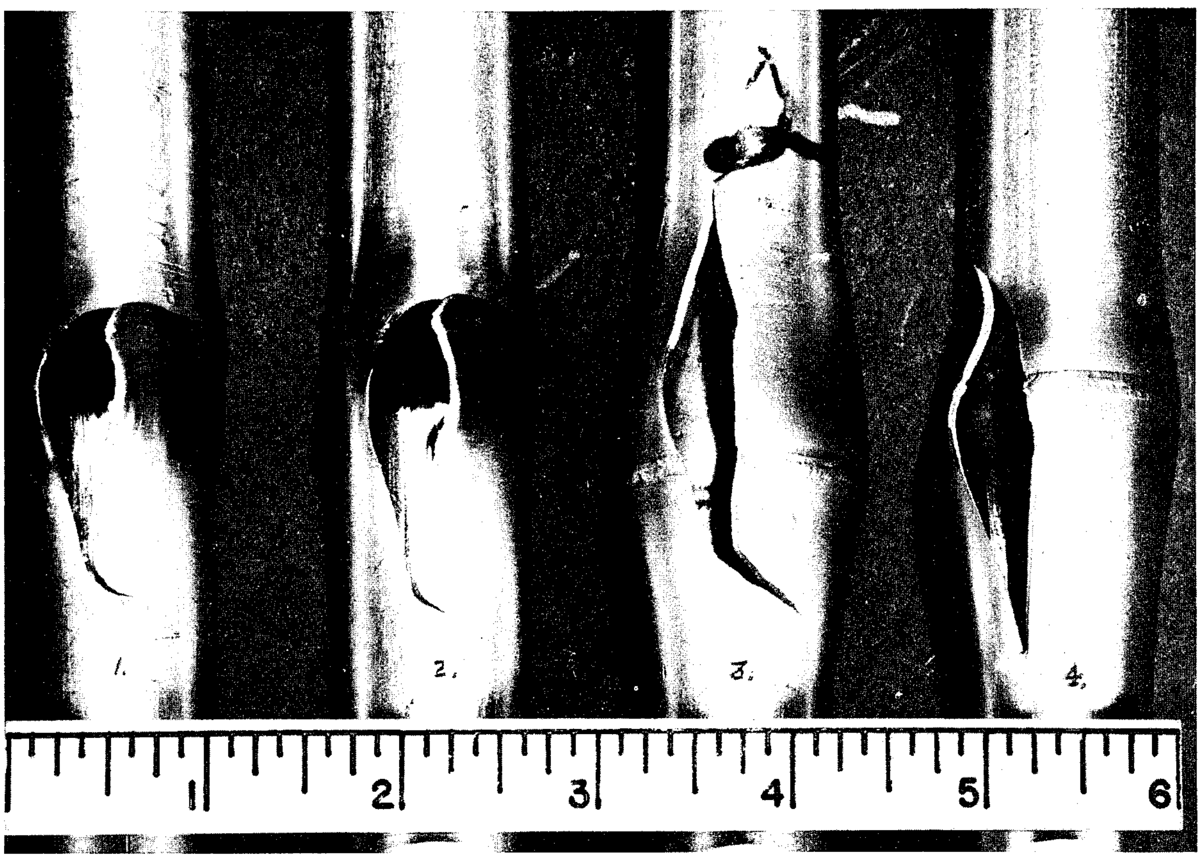

FIGURE II–7.—Burst-pressure test specimens, RT, of a 304L $.049\times1$-inch O.D. tube-flange weld.

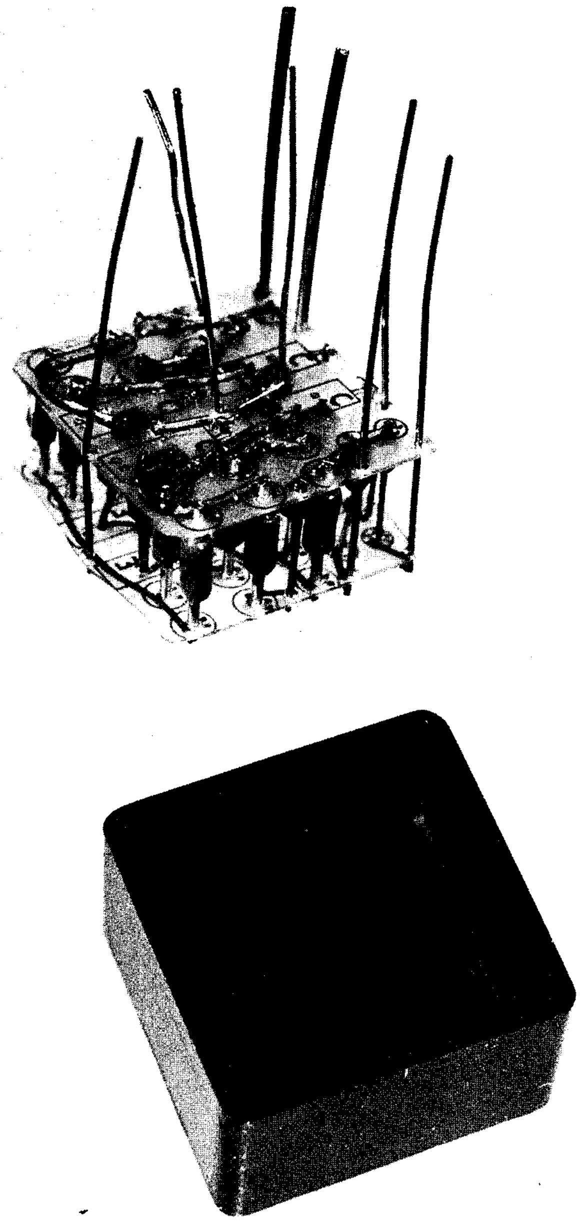

FIGURE II-8.—Resistance-welded high-density electronic modules.

SOLDER JOINTS

In addition to rigid compatibility and sealing requirements, another restriction is imposed by the low annealing temperature of aluminum alloys. This means that joining must be accomplished at temperatures below 600° F to assure maximum retention of parent-metal structural properties. Preliminary compatibility and sealing studies conducted by S&ID have indicated low-temperature-melting tin solders applied to joints preplated with nickel are possible sealant materials (ref. 5).

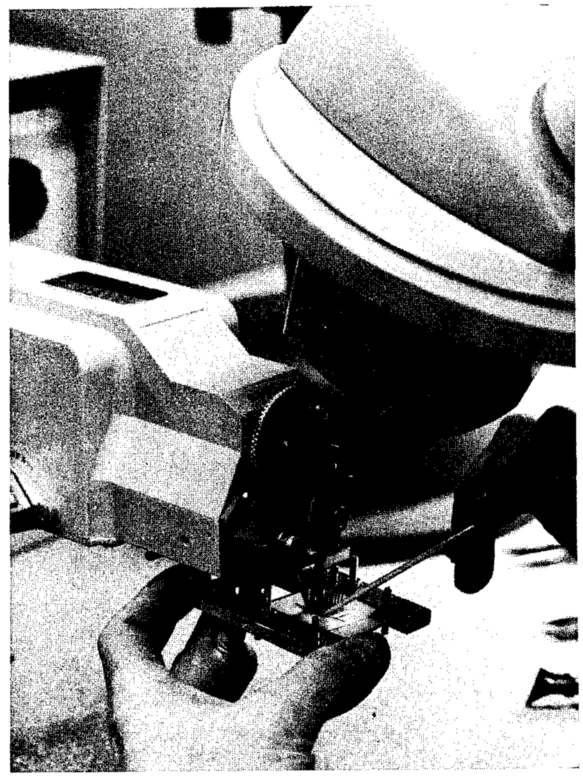

FIGURE II-9.—Resistance-welding apparatus.

ELECTRON BEAM

A relatively new electron-beam welding process is receiving considerable attention by fabricators. The parts to be joined are bombarded by a stream of high-energy electrons in a vacuum. As the electron stream hits the metal, most of the energy of the electrons is given up as heat. By concentrating the beam on a small area, sufficient heat is generated to melt the edges of the workpieces and produce a weld (ref. 6). Figure II-10 illustrates the apparatus used in the process.

The electrons are accelerated toward the weld joint by the voltage applied between a filament and the components or an anode placed between them. The energy imparted to the electrons, and subsequently appearing as heat in the workpiece, is largely determined by the applied

voltage. Electron-beam welders are available with voltage ratings ranging from 5 to 150 kilovolts. Actually, the commercially available welders generally are classed as low-voltage type (below about 30 kilovolts) and high-voltage type (up to about 150 kilovolts) (ref. 6).

The advantages of electron-beam welding are: (1) welding is done at high vacuum, so that weld-metal contamination from external sources is virtually eliminated; (2) deep-penetrating welds that have very narrow weld and heat-affected zones can be produced with high-power-density equipment; and (3) very precise control of welding variables is possible.

The narrowness of welds and heat-affected zones produced with a high-voltage-type electron-beam welder was demonstrated by one contractor. Single-pass welds were deposited in .095-inch-thick beta titanium by the TIG and the electron-beam welding process. The widths of the welds and heat-affected zones (HAZ) and the grain size of the welds were determined from micro- and macro-examination of weld cross sections. The results are shown in the following table taken from reference 6.

Welding process	Width of weld (inches)	Width of HAZ (inches)	Grain size of weld (inches)
TIG	.375-.438	.140-.180	.035
Electron beam	.060	.002	.010-.025

The depth-to-width ratio of the single-pass weld is much greater for the electron-beam deposit. This ratio may be as high as 20 for relatively thick material. This limited weld and HAZ site may have drawbacks. It was observed that the hydrogen content of electron-beam welds on beta titanium increased with decreasing weld-bead width, apparently because of the higher solidification rate. The finer

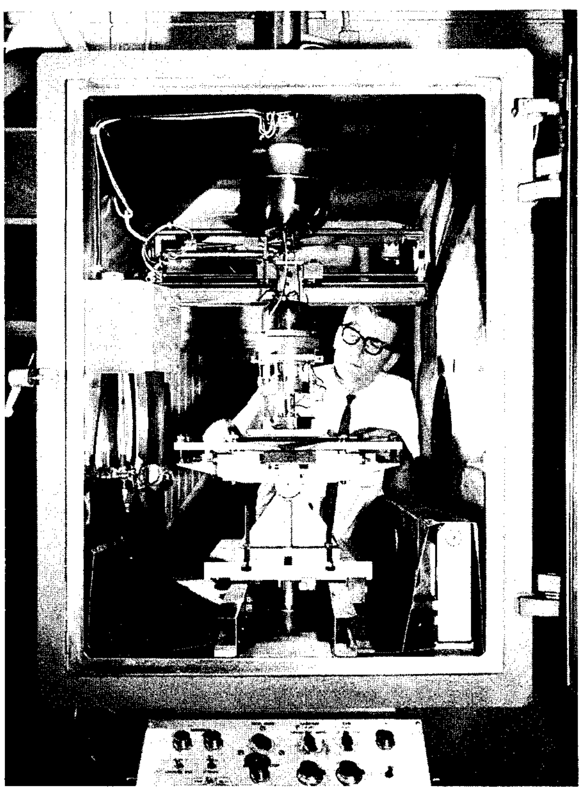

FIGURE II-10.—Electron-beam welder.

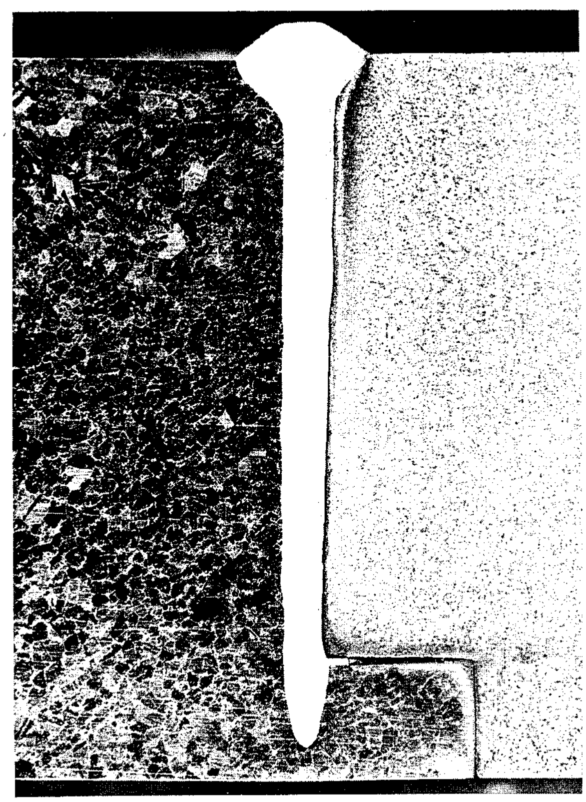

FIGURE II-11.—Electron-beam butt weld of udimet 500 to 4340 steel .675-inch thick.

grain size of electron-beam-welded specimens as compared with TIG-welded specimens probably accounts for the improved notched tensile strengths and fracture toughness of Ti-13V-11Cr-3Al weldments evaluated by this contractor (ref. 6). An electron-beam butt weld of an udimet 500 to 4340 steel .675-inch thick is shown in figure II–11.

PERCUSSION STUD-WELDING

Many types of stainless steels and aluminums can be percussion-welded, with studs of conventional or unusual sizes and shapes. It is applicable to joining various combinations of dissimilar-metal couples (ref. 7). Percussion welding is defined as "a resistance-welding process wherein coalescence is produced simultaneously over the entire area of abutting surfaces by heat obtained from an arc produced by a rapid discharge of electrical energy, with force percussively applied during or immediately following the electrical discharge."

In capacitor-discharge stud-welding, each stud has a small projection at its base. The stud is brought into contact with the parent metal. Then electrical energy, stored by charging capacitors with dc current at a preselected voltage, is discharged through the projection. The small projection presents a high resistance to the stored energy and rapidly disintegrates, creating an arc that heats the surfaces to be joined. During arcing, the pieces are brought together, and when the surfaces are in contact, fusion takes place and a solid bond is produced between stud and workpiece.

The chief advantage of percussion stud-welding is that studs can be welded from one side only and at a remote distance from the power supply. This has many applications, particularly for attachment to honeycomb-sandwich materials.

Studs can be welded to parts that have one side either plated, painted, or ceramic- or plastic-coated without marring or distorting the finished side. Additional advantages are the elimination of drilling and tapping required for other types of fasteners, and the elimination of leadage problems, because the studs are welded directly to the surface with negligible effect on material beneath the weld.

ULTRASONIC WELDING

Ultrasonic welding, though used primarily for aluminum joining at present, can be used for most metals, including dissimilar combinations such as titanium, zirconium, and thin gauges of beryllium and molybdenum. Spot, seam, and ring welds are made on materials of thicknesses ranging from less than .0002 inch up to .1 inch, the upper limit depending on the alloy and determined by the thinner piece (ref. 10).

The Theory and Process

The theory of ultrasonic welding is relatively simple. It was found that the close contact and friction developed with the passage of high-frequency vibratory energy through two abutting metals would cause them to adhere together without the use of welding current. In most cases, it is not necessary to apply heat (ref. 10).

The workpieces are clamped together under moderately low static force, and ultrasonic energy is transmitted into them for a brief interval. A metallurgical bond is produced without arc or sputter, without fusion of the weld metal, without the cast structure resulting from fusion, and with negligible thickness deformation (ref. 10). Figure II–12 shows ultrasonic welding equipment used by the Sonobond Corp.

Bimetal junctions of many materials are also feasible and practical. Aluminum can be welded to almost any of the above metals. Copper, brass, and steel can be welded to many of them. Combinations such as aluminum, copper, platinum, and gold to silicon or germanium are readily achieved. Other feasible bimetal welds include various combinations of molybdenum, nickel, tantalum, titanium, zirconium, and tungsten. Table III shows the possible dissimilar-metal combinations welded by ultrasonics.

Advantages

The advantages of ultrasonic welding have been repeatedly demonstrated in a variety of applications of interest to industry. Solutions to problems requiring high-strength joints be-

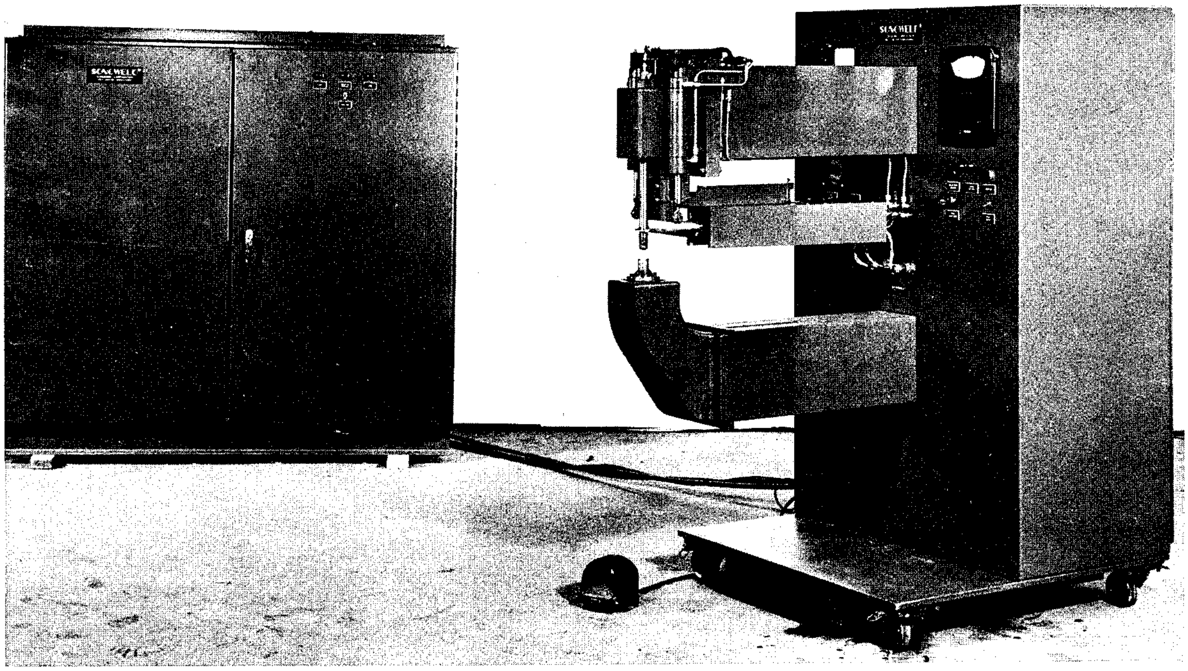

FIGURE II-12.—Ultrasonic welding equipment, Model W-4000—FSR, 400-watt; Sonobond Corp.

TABLE III.—*Dissimilar-Metal Combinations Welded by Ultrasonics (From Ref. 10)*

Metal	Aluminum	Copper	Germanium	Gold	Kovar	Molybdenum	Nickel	Platinum	Silicon	Steel	Zirconium
Zirconium	X	X				X				X	X
Steel	X	X				X	X	X		X	
Silicon	X			X							
Platinum	X	X		X	X		X	X			
Nickel	X	X		X	X	X	X				
Molybdenum	X					X					
Kovar	X	X		X	X						
Gold	X	X	X	X							
Germanium	X										
Copper	X	X									
Aluminum	X										

The presence of blanks does not necessarily mean that such a welding combination is impossible or impractical. In most cases the combination has not been attempted or studied.

tween similar and dissimilar metals have been achieved by ultrasonic welding, with significant improvements over conventional joining methods.

One recent development is the fabrication of all-welded, all-aluminum honeycomb by a leading metal fabricator. This honeycomb core is suitable as a structural material or as a thermal insulator at cryogenic temperatures. Other applications of welding thin foil aluminum and other metals may be developed to meet other space-vehicle structural requirements.

There is no apparent lower limit to the thickness of the materials that may be welded ultrasonically. This is possible because the heat generated by ultrasonic welding is minute in comparison to that required to produce sound welds by fusion or resistance-welding methods.

The temperature in the area of an ultrasonic weld usually does not exceed a value of about 35 percent of the absolute melting temperature of the metal involved. Since ultrasonic welding is a solid-stage process, fewer oxide, nitride, or other impure compounds are formed, with concomitant improvement in weld strength and ductility, and reduction in weld embrittlement.

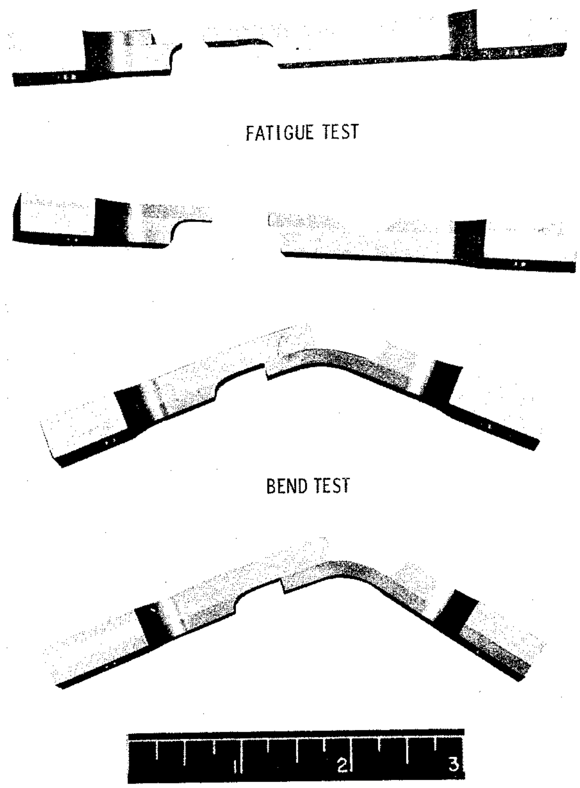

FIGURE II–13.—Bar specimens of roll-bond aluminum to stainless steel after fatigue and bend tests.

ROLL-BOND JOINING ALUMINUM TO STAINLESS STEEL

Alcoa Duranel plate, the product of roll-bonding aluminum to stainless steel, can be cut to any configuration. The steel portion of the bimetal can be welded to an extension of steel, and the aluminum to the aluminum part of the assembly. With this method, the Duranel bimetal plate is a transition piece from aluminum to steel. The sheet itself can be inspected for bonding by the ultrasonic method before it is welded in place, leaving only the inspection of the similar-metal welds.

The bonding mechanism that holds the stainless steel and aluminum together is mechanical; there is no indication of diffusion. When the Duranel is put in liquid hydrogen at −423° F, both metals shrink and the bond becomes stronger. Specimens were heated to 960° F, then quenched in oil and aged. When quenched from the high temperature, the aluminum transfers the heat 10 times as fast as the steel, so that some of the irregularities holding the two metals together shear, reducing the shear strength. After the maximum load, the bar extends. This indicates that the joint is not brittle. It actually has about 1.5-percent elongation.

The bend test, performed on bar specimens, was intended to show the degree of bend before peeling of the two metals was noticed. Both test bars bent 40 degrees before peeling. Other bar specimens were given a flex and a fatigue test on a Krause machine. This machine bends the specimen above and below the neutral axis. Specimens deflected ±.060 inches and were still intact after 3×10^6 cycles. The deflection was raised to ±.120. The part failed after 297,000 additional cycles. Figure II–13 shows bar specimens after the fatigue and bend tests. Table IV lists data on test specimens cut from the roll-bond plate.

TABLE IV.—*Data on Test Specimens Cut from Plate*

Test Bar No.	Type of test	Shear strength 1000 psi	Bend angle	Temperature of test	Cycles to failure	Deflection (inches)
1	Fatigue			Room	3×10^6 with no failure	±.060
1	Fatigue			Room	280, 000	±.120
2	Fatigue			Room	4, 300	±.120
3	Shear	13. 45		Room		
4	Shear	13. 58		Room		
5	Bend over 1 inch R		41°			
6	Bend over 1 inch R		42°			
7	Shear	9. 50	Heat-treated 960° F quenched in oil aged 8 hours at 350° F			
8	Shear	9. 95				
9	Shear	17. 05		−423° F		
10	Shear	16. 60		−423° F		

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III. The Usefulness of Aerospace Management Techniques in Other Sectors of the Economy

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Most of the unique management techniques or concepts used in the aerospace industry are associated with research and development, for this is the unique task of the aerospace industry. In looking at these techniques, we should keep in mind the peculiar conditions under which they evolved. The aerospace business deals with a problem that is quite different from that dealt with by conventional private industry.

Having considered these unique qualities, I want to turn my discussion to two problems that are a part of the knowledge-transformation process. First, how can companies oriented toward the civilian market make use of management techniques developed in the space-defense programs? And, second, what is the possibility for the present government contractor to utilize these peculiar capabilities in the non-government marketplace?

Turning first to the question of the unique conditions under which these techniques were developed, I think the most important single factor in the development of these techniques has been the fact that the contractor is dealing with the government as a customer. Because he is dealing with the government as a customer, he has a need for unusually concrete contracts, plans, specifications, etc. In fact, in many cases, the requirement for incentive contracts leads to the planning of activities that are conventionally thought of as unplannable. Invention and innovation must in some sense be scheduled. Having set forth these plans, there is the necessity of controlling the development process so as to achieve them or to come as close to achieving them as possible. An important pressure for control is the watchful eye of Congress and that of the Government Accounting Office, which seeks to insure that the taxpayers' money is spent with the greatest possible efficiency. In the private sector of the economy, there is much less need for such controls. The development process can proceed along more traditional, sequential decision-making lines. It is possible to start a development, carry it a short distance, and then make a decision to carry on, modify, or cancel the development. In the government, very often the goals are set at the very beginning of the development process, and a certain inflexibility occurs.

Secondly, to an unusual degree, the government contractor undertakes development in which large state-of-the-art advances are sought with unusual speed. This means that there is a need for scheduling breakthroughs. There is a willingness to trade a very great sum of money for a shortening of the development-time schedule. There is a willingness to take high-risk approaches that companies in the private sector of the economy simply would not be willing to accept. I mean technical risks, not financial risks, for the reason that

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the aerospace companies will undertake these risks is that the financial risks associated with the technical risks are largely taken by the government itself.

Thus the management techniques that have been developed are associated with this requirement for large state-of-the-art advances and development speed, and hence will have many qualities inappropriate to more typical developments in the non-aerospace industries.

The third unique quality of the aerospace-industry activity is the fact that many of the developments are very large developments by anybody's standards. It is seldom indeed that a private company undertakes a development that requires the expenditure of half a billion dollars. The implication of this is, I think, primarily that a development in the aerospace industry rapidly gets out of the span of control of a single, unaided individual. There is a need for sophisticated information systems, which attempt to extend the capabilities of individuals in charge of development projects. Moreover, there is a complicated welding together of divergent technologies in most of these projects, which requires a means of communication between the practitioners in these different technologies. The very size of the project means that the companies must have information systems that will deal with rapid increases in work force and, subsequently, rapid decreases in work force.

Another factor differentiating the aerospace industry's activities from the rest of the economy is the peculiar kinds of constraints that exist. In the aerospace industries, money has frequently been almost the least significant development constraint. For example, traditionally, weight has been a terribly important factor in all aerospace developments. It costs $10,000 to place a pound of weight in orbit. It costs a great deal of money to carry around an extra pound of airframe weight. Hence, the reliability techniques that have grown up in the industry have not emphasized saving money, or funding the most economical means of achieving a given reliability, but, rather, funding the lowest-weight alternative for achieving a given reliability. Of course, the ultimate motivation to minimize weight is economic, but the narrow techniques themselves frequently are designed to minimize weight as a rule-of-thumb criterion. Accordingly, the most usual and useful engineering technique for achieving greater reliability—the use of additional weight and large safety factors—has been eliminated.

Finally, in the aerospace industry in general, there is a lack of a good criterion for measuring the value of a project or of project changes. There is no market test for the value of additional pounds of thrust in a rocket engine or additional pounds of payload that can be carried into orbit. The value of these increments of performance are matters of judgment or of artificial analyses. Thus it is very difficult to subject proposed changes in a project to an intelligent analysis of the benefits to accrue to these changes when they are judged in the light of the cost of making the changes; and surely the information systems developed in the industry reflect this fact.

What, then, is the possibility for the transference of these techniques, or some of these techniques, to the non-aerospace industry? I think it should be clear that few of these techniques can be transferred unchanged. They were developed for particular purposes and under particular conditions, which I have tried to outline, and it would be surprising indeed if they fit exactly into industries that function under quite different conditions. Yet the non-aerospace industry has great flexibility. There is no need for its members to adopt the techniques in full. There is no contractual requirement that they use techniques in a particular way. They have the option of picking and choosing those parts of a technique that make the most sense to their operation.

Another point to recognize is that the very complexity of many of these management techniques reflects the very great uncertainties that exist in the development process as practiced by the aerospace industries. These uncertainties, as we have pointed out, arise from the attempt to take very large leaps in the state of the art simultaneously with extreme time compression. It may well be that much of the complexity of these techniques can be eliminated when they are used in tasks that have

less uncertainty associated with them. Perhaps substantial parts of the procedure can be eliminated while still retaining the essential features of the technique.

Finally, I think that studies of the techniques used in the aerospace industry and of the development process in the aerospace industry would provide valuable insights into the development process in non-aerospace firms. In a sense, a study of these developments makes the same sort of contribution to an understanding of the normal development process as a study of abnormal psychology does to an understanding of ordinary human behavior.

Turning to the problems of present government contractors who seek to enter non-government markets, I would like to emphasize the point that it takes two qualities to make an innovation. The first is a perception of the need or demand for a product. And the second is a conception of the way in which to meet this need. Traditionally, the perception of the need has come first, and the seeking out of technologies or the way in which to meet this need or demand has followed.

We are attempting in some sense to turn this process around. Instead of having demands or needs searching for technology to satisfy them, we have lots of technology, and the technology is in search of the need. It would not be surprising if the approach to development and the way in which we feel it is appropriate to communicate technical information should change quite radically under these new conditions.

As an example of the importance of an understanding of the final-product area, I would like to examine briefly the development of the jet aircraft engine. This development is discussed in some detail in the book by Robert Schlaiffer, *Development of Aircraft Engines.* The technology utilized in the initial aircraft jet engines was largely developed by the makers of stationary powerplants. They were the ones who understood and had investigated the aerodynamics of turbine blades. They were the ones who had some feeling for the efficiencies that could be achieved, and appreciated the useful qualities of such devices. It was from these people that many of the initial proposals for the aircraft jet engines were obtained. However, it was not until the old-line aircraft-engine companies, such as Rolls Royce and Pratt and Whitney, were brought into the development picture that a truly useful device came out. The reason for this was not hard to see. These companies had a perception of the requirements for durability and light weight, and knew how to achieve these requirements, which simply was not a part of the understanding of the stationary-powerplant manufacturers. The stationary-powerplant manufacturers thought in terms of durabilities of 20 to 30 years. A modern jet-aircraft fighter will be unusual if it flies more than a couple of thousand hours in a lifetime.

The stationary-powerplant engineers were not familiar with the techniques used to test and obtain the requisite light weight with the appropriate amount of durability. That was the very talent that was brought to the development process by Rolls Royce and Pratt and Whitney. The one exception to this pattern was the development of the engine by the General Electric Company. GE not only had experience with stationary powerplants but had been in the business of supplying superchargers for piston aircraft engines, and therefore had some understanding of the aircraft-engine requirements. Thus, if the aerospace industries seek to take their technology (and I would include with technology their managerial techniques) into other industrial areas, it will be folly for them to do so without having or acquiring an understanding in some depth of other product areas. My guess would be that this will have to be done by the acquisition of firms familiar with these product areas.

It must be recognized that the aerospace industry has grown up in this environment in which the customer has been able to demand and receive very extensive amounts of information. The reporting devices, the information and control systems, have been geared to provide the customer with this information, regardless of additional effectiveness in the conduct of the development or production process. If the aerospace industry goes into other industries, attempts to produce other kinds of products, it must very carefully examine the man-

agement systems to see that the cost of the additional information they obtain is commensurate with the value of this information. It will be extremely difficult to cut back on the flow of the information, because the managers of the aerospace companies have become accustomed to working with such data. Their decisions may not be better, but, as a result of much of these data, they may be far more comfortable in making the decisions.

There are other problems that occur. We noted that the aerospace industry has a unique capability, in the sense that it traditionally has worked by welding together a number of separate technical disciplines. It has developed an ability to communicate between these disciplines. In many other areas, less specialized than the aerospace industry, the returns to specialization and the utilization of individual experts may not outweigh the costs of this specialization. It is not often appreciated just how expensive it is, both in terms of dollars and of decision delay, to coordinate the work of a group of specialists who cannot communicate effectively with one another.

But the aerospace industries do have some comparative advantages. They are able to manage and are familiar with managing extremely large projects. They are able to work under conditions in which there is high technical risk, conditions that might very well frighten companies less accustomed to this situation. They are familiar with the simultaneous development of both a product and the processes that build the product. They are able to reflect in these new products considerations of maintainability, reliability, and manufacturability. Finally, they have an ability to be extremely flexible in the production process, for in many respects their production facilities are simply large job shops. They have a capability to schedule a great variety of projects through their shops, in a manner that most other industries are not set up to do.

In summary, the managerial techniques used in aerospace companies have been shaped by the unique conditions surrounding the industry. The demands of their most important customer, the government; the frequent combination of large state-of-the-art advances with great development urgency; and the large size of many projects have combined to shape management techniques and systems. I have suggested that these techniques cannot be translated or transferred into other industries without extensive modifications, and yet there are many qualities similar to processes that appear in other industries, and a selective utilization of some parts of the managerial techniques is likely to have a very profound and useful effect upon other industries. It is not a simple matter to transfer these techniques to other industries, and such a transfer will not occur unless the manager in those industries seeks out those components of the managerial systems that make sense to him.

IV. Advances in Pumping Technology and Rocket-Engine Turbopump Applications

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This report is divided into two general parts. The first part is a description of turbopumps for liquid rocket engines as they exist today. For completeness and understanding, some background information is included on why turbopumps have evolved to their present configurations. The second part suggests portions of this effort that may have some applicability to the general economy.

TURBOPUMP FOR LIQUID ROCKET ENGINES

Turbopump Characteristics

Function.—The turbopump has the distinction of being one of the most important components in a liquid rocket engine. Its function in an engine installation is to receive propellants from the tanks and deliver them to the thrust chamber at design pressure levels and flow rates, so that the engine can develop design thrust at the required chamber pressure. The turbopump is rotating machinery assembly consisting of a pump (or pumps) for increasing the pressure level of the propellant(s). The power to drive the pump(s) in this assembly is supplied by a turbine, which utilizes working fluids supplied by the engine-system gas generator. Turbopump design configurations can vary depending on the engine combustion process, the installation requirements, and the propellants being pumped. Detailed descriptions of turbopump configurations will be presented in the following text.

Fluids and fluid properties.—The major factor influencing the type of turbopump design chosen for any application is the density of the propellants to be pumped. Variations in oxidizer and fuel density require the individual pumps to be operated at speeds capable of obtaining respective pump-head and volume flows. A tabulation of propellant properties, which shows the variation in propellant densities, appears in table I.

For turbopumps pumping propellant combinations that have similar densities, both pumps can be run at the same speed. In cases where a great variation in propellant density exists between the oxidizer and fuel, as in the liquid oxygen (LOX)/liquid hydrogen (LH_2) combination, each pump is driven at its best design speed to meet individual head requirements most efficiently.

Operating range.—Figure IV–1 is a plot showing the range of operation for typical propellant pumps in terms of pump head and flow. This curve demonstrates how the head requirements for the less dense propellant, liquid hydrogen, are much greater than those required by either liquid oxygen or RP–1. The plot shown in figure IV–2 is the operation envelope of current turbopump-turbine designs, based on power and speed requirements. Turbine working-fluid mass flow rate depends on the properties of these fluids, the power-development requirements, amount of energy from these fluids made available to the turbine to convert into work, and the turbine design and operating parameters. A list of working-fluid properties for common propellant combinations appears in table II. As power requirements for a specific

TABLE I.—*Fluid Properties (Liquid)*

Liquid	Data at Normal** Conditions			
	Temperature, °F	Vapor pressure, psia	Density, lb/cu ft	Viscosity × 10^7 lb-sec/sq in.
N_2O_4	60	11. 1	90. 88	0. 657
N_2H_4	60	0. 152	63. 25	1. 49
H_2O	60	0. 255	62. 37	1. 65
RP–1	60	0. 01	50. 45	5. 51
Ethyl-Alcohol (95 percent— 5 percent)	60	0. 652	50. 44	2. 247
UDMH	60	1. 89	49. 71	0. 845
LOX**	−297. 5	14. 6	71. 39	0. 277
LFL	−305	16. 0	93. 77	0. 338
LN_2	−315	20. 70	49. 50	NI
LH_2	−425	10. 62	*4. 42	0. 0206

*Density at 14.7 psia.
**Normal conditions do not necessarily imply standard conditions, if tank pressures have been applied.

design operating point increase, the ratio of turbine mass flow rate to engine flow increases. If chamber pressure is increased for a fixed thrust condition, the turbine power requirements to develop the needed pump heads become greater. A plot of turbine-to-engine-weight flow ratio vs. chamber pressure for a gas-generator installation is shown in figure IV–3. The curves for both LOX/RP–1 and LOX/LH_2 clearly show that as design chamber pressure is increased, the turbine-to-engine-weight flow ratio increasingly influences engine performance. The effect of chamber pressure on turbopump weight is also an important design consideration. To meet the increased power requirements for higher chamber pressures, the turbopump assembly weight becomes heavier. A plot showing the effect of chamber pressure on the turbopump-to-engine-weight ratio is shown in figure IV–4.

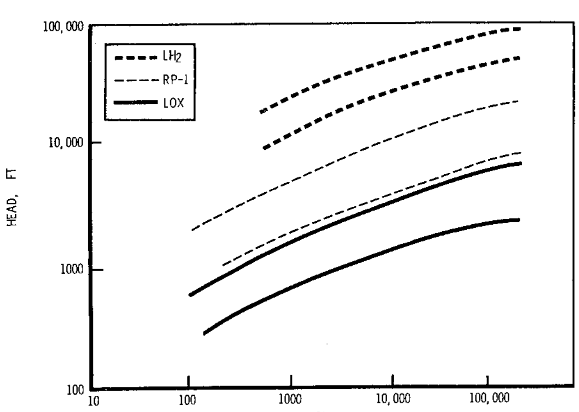

FIGURE IV–1.—Range of operation for typical propellant pump.

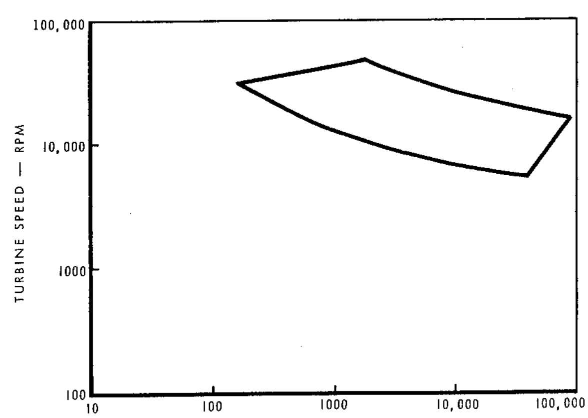

FIGURE IV–2.—Operation envelope of current turbines.

TABLE II.—*Gas Properties*

Fluid	Inlet temperature, °F	C_p, Btu/lb °F	γ	R, ft lb/lb °F	Mixture ratio, o/f
LOX/RP-1	1100	0. 635	1. 097	43. 3	0. 303
	1150	. 639	1. 100	45. 1	. 320
	1200	. 643	1. 106	47. 1	. 337
	1250	. 646	1. 111	58. 6	. 354
	1300	. 648	1. 115	50. 4	. 372
	1350	. 651	1. 119	51. 8	. 390
	1400	. 653	1. 124	53. 6	. 408
	1450	. 655	1. 128	55. 4	. 425
	1500	. 657	1. 132	58. 0	. 443
	1550	. 659	1. 137	59. 0	. 460
	1600	. 660	1. 140	60. 7	. 478
	1650	. 661	1. 144	62. 4	. 497
	1700	. 662	1. 148	64. 0	. 516
N_2O_3/CH_3 (UDMH)	1400	. 380	1. 42	87. 5	. 11
	1500	. 398	1. 42	91. 6	. 165
	1600	. 416	1. 42	95. 7	. 22
	1700	. 434	1. 42	99. 9	. 274
	1800	. 452	1. 42	104. 0	. 328
	1900	. 470	1. 42	108. 2	. 382
LOX/LH_2	1000	2. 05	1. 374	434	. 785
	1200	1. 94	1. 364	403	. 903
	1400	1. 86	1. 354	378	1. 025
	1600	1. 80	1. 343	358	1. 143
	1800	1. 73	1. 333	336	1. 273
	2000	1. 69	1. 322	320	1. 410

Turbopump-Design Process

The process of designing a turbopump is shown graphically in figure IV–5. The influences of the various quantities that must be considered and determined are shown so that the turbopump can be specified graphically and analytically. It is through this process and by considering these items that the various turbopump designs have evolved.

Turbopump-design criteria.—In selecting a

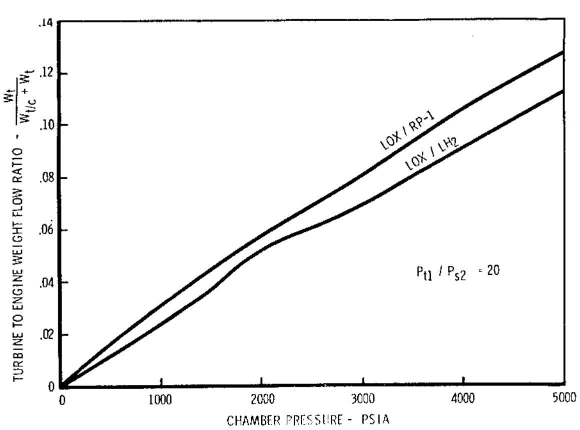

FIGURE IV–3.—Turbine-to-engine weight flow ratio.

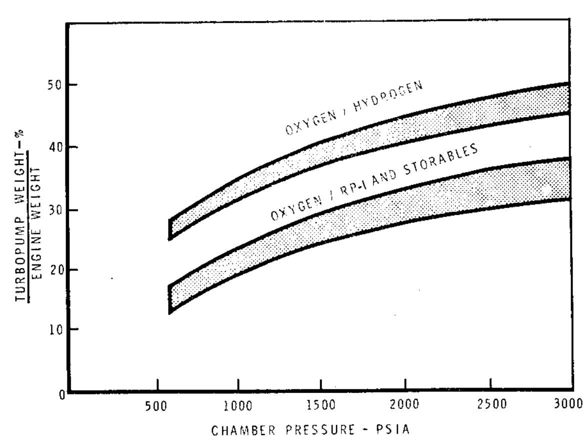

FIGURE IV–4.—Effect of chamber pressure on relative turbopump weights.

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turbopump-design geometry, it is necessary to have a set of criteria by which to establish the desirability of a configuration. The criteria used for this selection are classified as reliability, flexibility, ease of development, weight, and performance.

The most important single criterion is that of turbopump reliability. It defines the expected successful performance of the turbopump in meeting the requirements of the design. Experience has shown that good reliability is a function of using design principles and techniques that are simple and provide a sound basis for performing the mechanical function for which the machine is designed. In addition to simplicity of design, the reliability of a machine depends on utilizing as few detail parts as necessary to perform the job intended by the design.

A turbopump design must incorporate the characteristic of flexibility toward operating under a wide variety of conditions. This flexibility must include ability to deviate from the design operating point, ease of the unit to provide a base from which it can be uprated to provide a higher level of performance, and also provision for changing individual pump operating points to facilitate adjustments in engine-mixture ratio.

The criteria that provide for ease of development for a turbopump configuration are of major importance. These include the manufacturer's experience and ability in fabricating and successfully testing a new turbopump design, the existence of knowledge to perform the program, and ability to predict the magnitude and time of the development program. Another important consideration affecting ease of development is the ability to predict performance. This capability provides for a

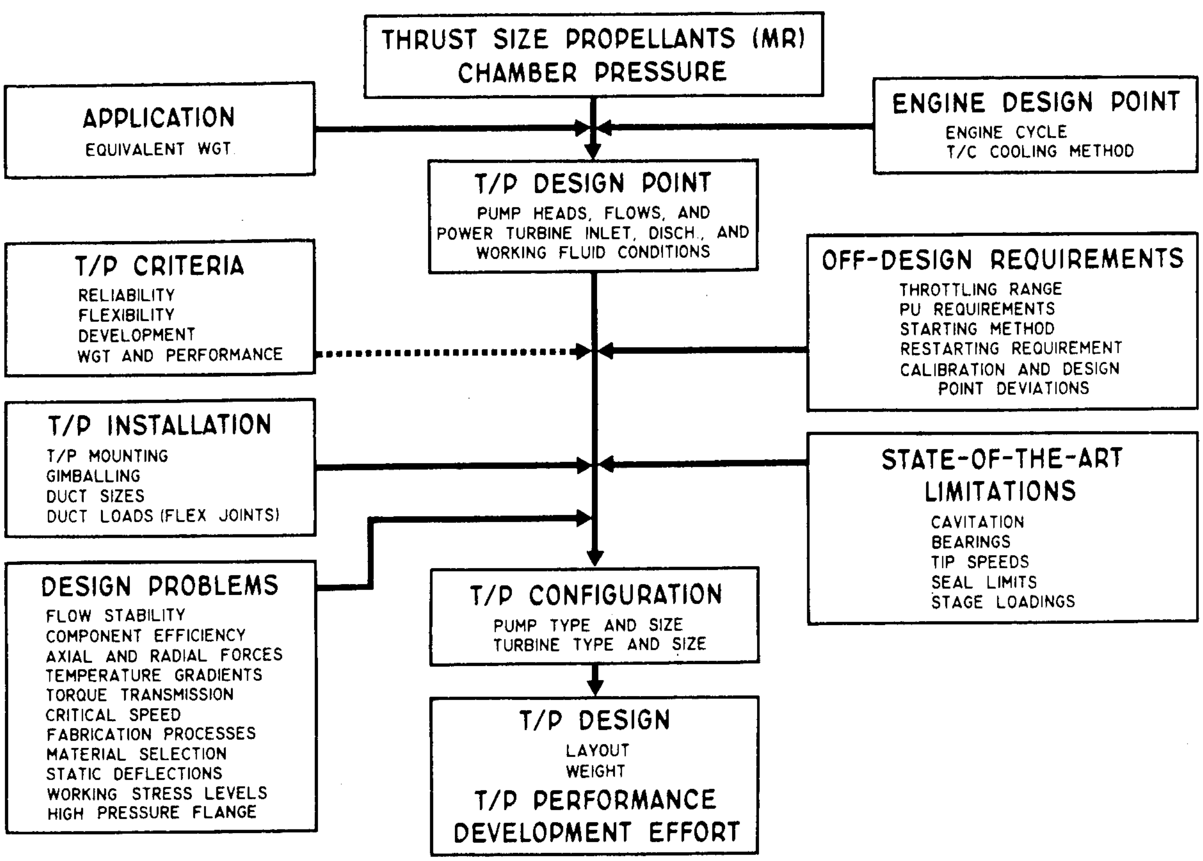

FIGURE IV-5.—Turbomachinery design process.

prototype design that requires a minimum of modifications and obtains the desired program objectives in a shorter development-time period.

The prediction of turbopump dry weight and performance can be combined in terms of equivalent weight; i.e., the turbopump dry weight is added to the weight representing the equivalent propellant weight consumed by the turbopump, expressed in terms of initial missile-payload weight. This criterion is the least difficult to predict analytically for a new design application.

Turbopump-design requirements.—To meet the requirements of a specific engine application satisfactorily, the turbopumps in many of the new engine designs, in addition to operating at steady-state conditions, must have the capability of throttling engine thrust to meet specific mission requirements. The design also must have the flexibility to be used with different engine-starting methods. This can vary from use of propellant tank head to start the pumping of propellants to the thrust chamber to perhaps a turbine-spin start from an auxiliary power source. With any start sequence, the pumps must smoothly develop required heads and flows without cavitating or transmitting pressure pulses through the propellant supply system. Additional requirements that may be imposed on a turbopump are those of providing engine restarts in flight or varying engine-mixture ratio in flight operation so that all the propellants in the tanks can be utilized during the flight mission.

Design problems and solutions.—Turbopump experience has shown that there are basic design problems that must be considered and solved before a new configuration will meet required operating specifications satisfactorily.

The individual pumps will be required to demonstrate stable performance characteristics for the full operating range of the turbopump without tending to cavitate, transmit pressure pulses to the propellant feed system, or go into a region of stall. Development tests are conducted with both air and water, using pump detail inducers, impellers, and pump subassemblies at a pump-component test facility to ascertain that the pumps will perform satisfactorily before being used in a turbopump assembly. Comparable tests are conducted with the turbine at a turbine test facility.

Attaining the individual efficiencies of components used in the turbopump can be a trouble source in qualifying a new turbopump design. To ensure that the units are operating at required performance levels, all components are fully developed for the full range of operation in component test facilities prior to their use as turbopump production configurations.

Loads arising from axial and radial forces can reach proportions capable of causing internal damage because of rubbing of rotating parts. In extreme cases, complete failure of the turbopump by explosion can be experienced if the propellant being pumped has the properties of liquid oxygen. To eliminate such problems, the pumps are designed with balance pistons, and with provisions to distribute pressures evenly within the pumps. The work with bearings capable of withstanding larger radial and axial loads is aimed at helping to minimize this type of problem.

Considerable work has been done to eliminate problems caused by temperature gradients within the pump. With a cryogenic-turbopump design, it is possible to have a pump operating at a temperature less than −300° to −400° F mounted adjacent to a turbine operating with working-fluid temperatures ranging from 1200° to 1700° F. This environment and temperature gradient presents problems with differential contraction and expansion, lubrication, and sealing. Cryogenic-turbopump design and development experience have established techniques for cooling and allowing for thermal growth between adjacent components.

Problems associated with fabrication processes for new turbopump design configurations are dealt with by two approaches. Primary considerations are given to the design of a component to determine if the complexity of the unit could be simplified and still perform in the same manner. If the design is committed to fabrication, the individual casting, forging, and machining processes and techniques are improved or developed so that parts can be produced with consistent quality. In some difficult instances, either the mode of fabrication or the material is changed. Casting

processes for new pump volutes are often developed so that the volute casting will be of acceptable quality.

Experience with selecting materials for fabricating new turbopump hardware has shown that newly developed alloys with properties suitable for turbopump service often present machining problems. In most cases, all such problems were eliminated as machining experience with the new alloy was accumulated. When selecting materials for fabricating a new component, those common materials that have been worked with previously are investigated first, rather than using a new, exotic type with properties that far exceed the maximum requirements for the application.

There have been instances when problems associated with torque transmission and critical speed have had to be solved in turbopump development programs. One method of minimizing the problems of transmitting torque (for example, from the turbine to the pumps) has been to utilize curvic couplings in the designs. They have proved very satisfactory in service. In checking new turbopump designs, the critical speed in bending is analyzed for the rotating assembly. For designs that operate above the first critical, the calculated first critical should be no more than 85 percent of the design speed. For the case of operation below the first critical, the calculated first critical should be no less than 150 percent of the design speed.

Turbopump state-of-the-art limitations.—Turbopump state-of-the-art limitations represent the existing boundaries to man's knowledge concerning turbopumps. Exceeding any one of these limitations will result in a turbopump that is either unreliable or inefficient.

Rocket-engine turbopumps are designed at the maximum allowable rotational speed because of weight considerations. Figure IV–6 demonstrates this relationship between turbopump weight and rotational speed.

Each stage of a rocket-engine pump delivers as much work as the structural and hydrodynamic limitations will allow, because the number of required stages is inversely proportional to the work delivered per stage. This minimizes the pump weight, because pump weight increases with the number of required stages.

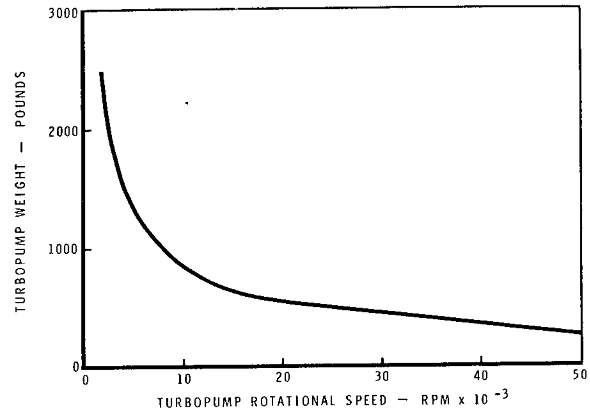

FIGURE IV–6.—Turbopump weight versus rotational speed. The pump pressure rise is 2,000 psi and the pump flow rate is 10,000 gpm.

Existing Limits

The following hydrodynamic and structural phenomena place an upper limit on rotational speed and a lower limit on the number of pump stages.

Cavitation.—Cavitation within a pump is the passage of the pump flow from the liquid phase to the vapor phase. This severely restricts the weight flow delivered by the pump, because of two interacting reasons: (1) the volume flow rate delivered by a pump is constant, and (2) a vapor occupies a much larger volume than the corresponding liquid. Cavitation also will cause severe erosion of the flow passages in a pump that operates for long periods of time, because the vapor cavity collapses violently when it passes into a higher-pressure region. This erosion is a minor consideration in rocket-engine pumps, because these pumps have a very short operating duration.

These adverse effects of cavitation are minimized by attaching an inducer upstream of the main impeller inlet. This inducer raises the pressure of the pump flow to a level at which the flow will not cavitate within the impeller.

An inducer will operate satisfactorily at low pressures because it is designed to avoid low-pressure regions within the flow passing through it. Figure IV–7 is a photograph of a typical inducer. It is a small axial stage with a large inlet area and a small number of very thin,

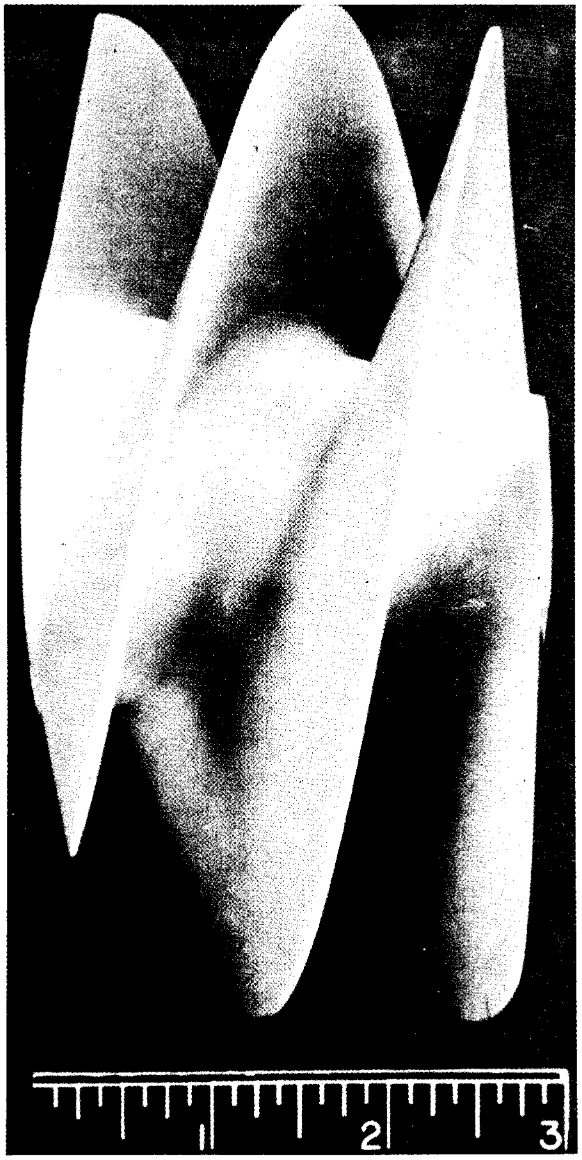

FIGURE IV–7.—Typical turbopump inducer.

low-cambered blades. This type of design avoids low-pressure regions by minimizing the relative velocity of the flow as it passes over the blades.

Bearings.—The speed limit of rolling contact bearings is expressed by the parameter DN. This parameter is directly proportional to the tangential velocity of the shaft OD, and is the product of the diameter (in millimeters) of the shaft that passes through the bearing, and the shaft rotational-speed rpm.

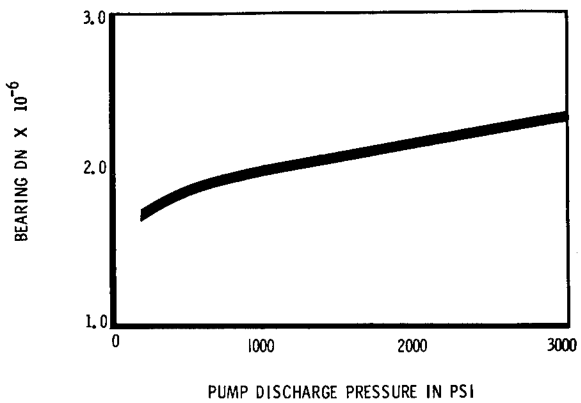

FIGURE IV–8.—Bearing speed versus pump-discharge pressure. The propellant is LH_2 and the flow rate is 10,000 gpm.

Depending on the lubricant, the DN limit for rolling contact bearings is in excess of one million (see fig. IV–8). Operation at higher DN values will cause contact fatigue in the outer race and excessive heat generation. These modes of failure are caused by high centrifugal forces and nonrolling phenomena, respectively.

Rocket-engine turbopump bearings are lubricated by the propellant being pumped. This eliminates a separate lubrication system and reduces sealing problems. Explosions can occur if separate lubricants are used and they mix with the propellants.

Seals.—The function of a seal is to minimize or prevent the leakage of a contained fluid by presenting a high resistance to flow along any potential leakage path. This is accomplished in rotating machinery by mechanically forcing the seal face against the surface of the rotating element.

The velocity at which the seal face rubs against the rotating element has an upper limit (depending on the liquid being sealed) in excess of 300 fps (see fig. IV–9). Operation at higher velocities will generate excessive heat, which will reduce the cooling capacity of the surrounding liquid by vaporizing it. The result of such operation is a rapid temperature rise followed by failure.

Structural limitations.—The centrifugal stress at the root of the turbine blades can limit the turbopump rotational speed. This stress is

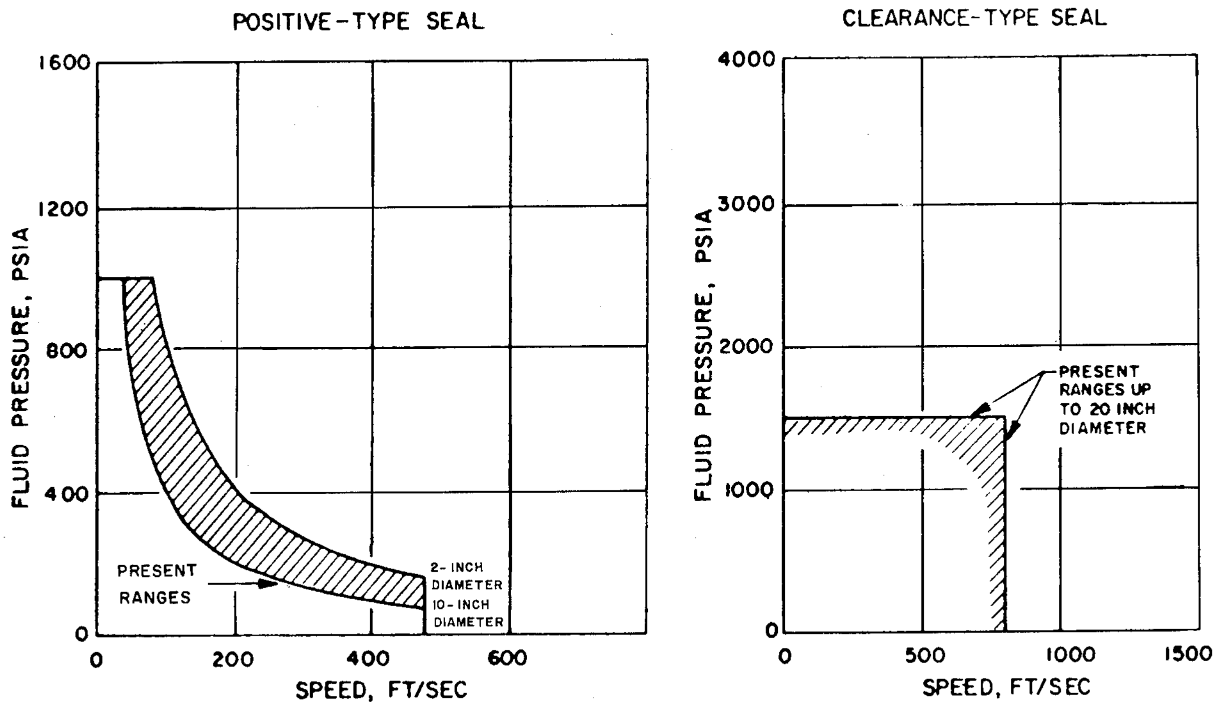

FIGURE IV-9.—Positive and clearance seal operating requirements.

proportional to the product of the maximum turbine annulus area and the square of the speed. Therefore, the maximum speed allowed by this limitation is set if the turbine flow rate, inlet conditions, and horsepower are specified, because these parameters set the annulus area.

The amount of head rise per shrouded centrifugal stage is limited by a maximum allowable tip speed of 2200 fps if the impeller is made of titanium. Higher tip speeds will cause yielding in the impeller, because the centrifugal stresses will be excessive. Unshrouded centrifugal impellers can operate at higher tip speeds, but have lower efficiencies and excessive axial forces.

Hydrodynamic limitations.—The blades of an axial pump stage should turn the flow as much as possible, because this maximizes the amount of work put into the fluid per stage. This minimizes the pump length by minimizing the number of stages.

The turning is limited by the maximum allowable-diffusion factor. The rotor-diffusion factor is defined as follows (referring to fig. IV–10):

$$D=1\ \frac{W_2}{W_1}+\frac{W_{u_1}-W_{u_2}}{2\sigma W_1}$$

where

$$\sigma=\frac{s}{c}$$

The stator-diffusion factor should be similar, because efficiency considerations make 50-percent reaction staging desirable.

Blading with a diffusion factor of 0.7 will perform well. This has been demonstrated by

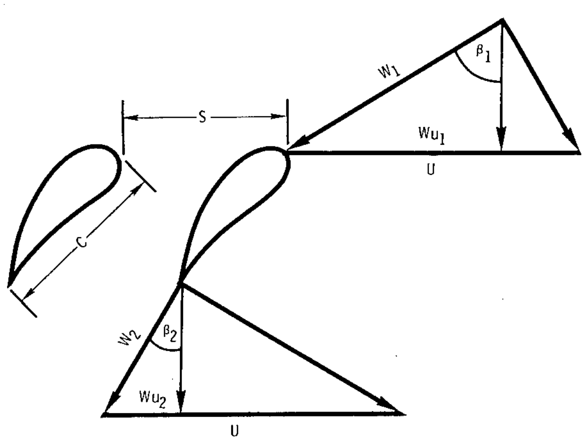

FIGURE IV-10.—Blade velocity diagram.

experimental testing at Rocketdyne. Loading in excess of this value, however, can result in low pump efficiency from flow separation within the blade row.

Diffusion problems within centrifugal impellers can be alleviated by using backward-curved vanes. This will reduce the diffusion within the impeller passage, because the tip relative velocity will have a backward tangential component as well as a radial component.

Influence of the Limits

The influence of these limits on turbopump rotational speed is demonstrated in figure IV–11. The specific speed limit indicates the maximum speed at which a centrifugal pump can be operated. Axial pumps must be used if this limitation is to be exceeded, because this limitation indicates that the impeller-inlet diameter is almost equal to the impeller-tip diameter. Seal speed and bearing DN limits are evaluated for shafts that are sized by critical

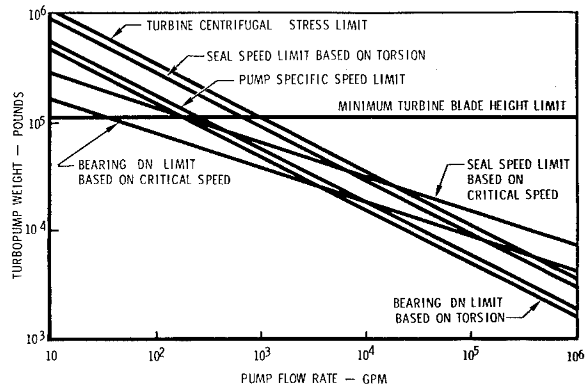

FIGURE IV–11.—**Maximum rotational speeds allowed by various limits.**

speed considerations and by the torsional-stress limit.

Turbopump Configurations

Turbopumps can be designed into a number of different configurations and arrangements. The final selection depends on the desired

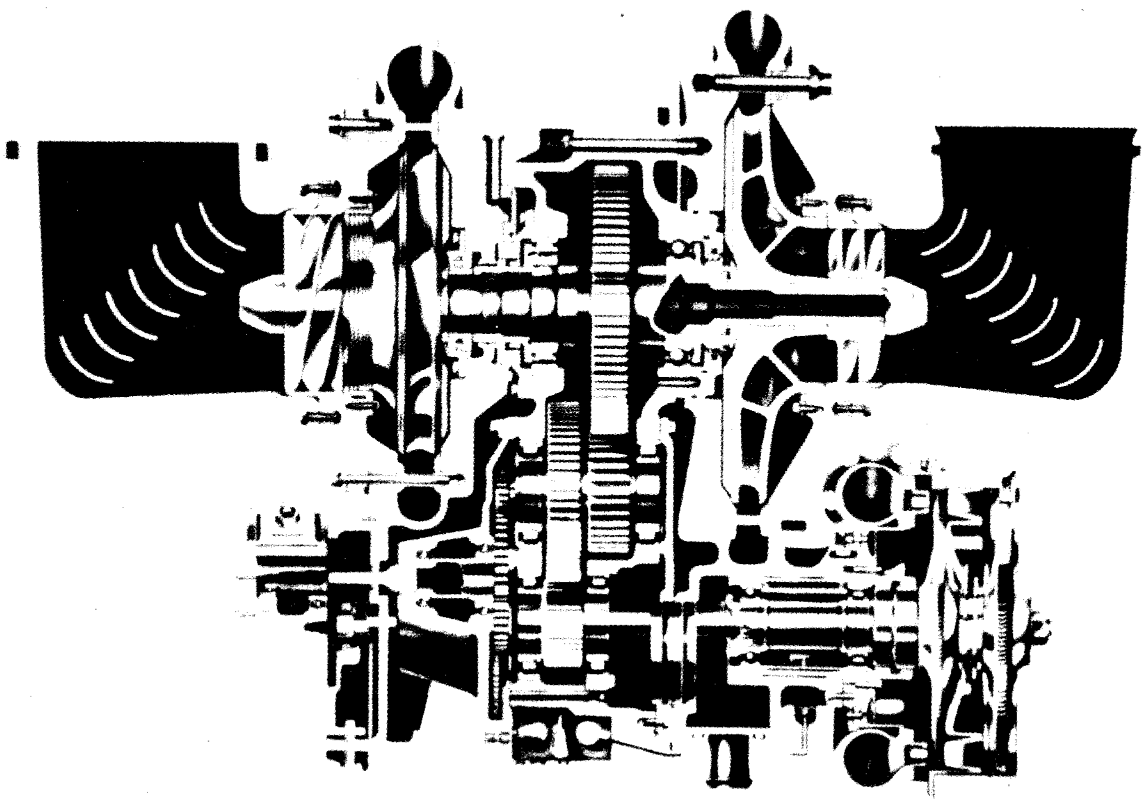

FIGURE IV–12.—**Geared turbopump.**

speed ratio between pumps, the arrangement of components, and the energy source of the turbine working fluid. There are three basic turbopump design types:

(1) Geared turbopump
(2) Single-shaft turbopump
(3) Dual-shaft turbopump.

Geared turbopump.—The geared-turbopump design configuration utilizes a gear box with which to drive the fuel and oxidizer pumps at different speeds with a single turbine drive assembly. Figure IV–12 contains a cutaway photograph of a LOX/RP–1 geared-turbopump configuration that is currently in service in a booster engine of 150,000-lb. thrust.

Single-shaft turbopump.—The turbopump photographs shown in figures IV–13 and IV–14 are of single-shaft turbopump configurations. In this type of design, both the oxidizer and fuel pumps are driven on one shaft by a single turbine. The turbopump shown in figure IV–13 is for an engine rated at 70,000-lb. thrust. The single-shaft turbopump assembly shown in figure IV–14 is being used in LOX/RP–1, 1,500,000-lb.-thrust engine.

Dual-shaft turbopump.—The dual-shaft turbopump configuration utilizes separate shafts to drive the oxidizer and fuel pumps at the best speed to meet the head and flow requirements of the propellants being pumped. Each pump is driven by its own turbine. Pump speeds, heads, and flows can be adjusted independently with this type of pump installation. Dual-shaft configurations are used for pumping propellant combinations that have large differences in density; for example, LOX/LH_2. Photos shown in figure IV–15 are of dual-shaft, LOX-and-LH_2 turbopumps, respectively, for a 200,000-lb.-thrust engine application. In dual-shaft installation, the turbines can be installed either in series or in parallel.

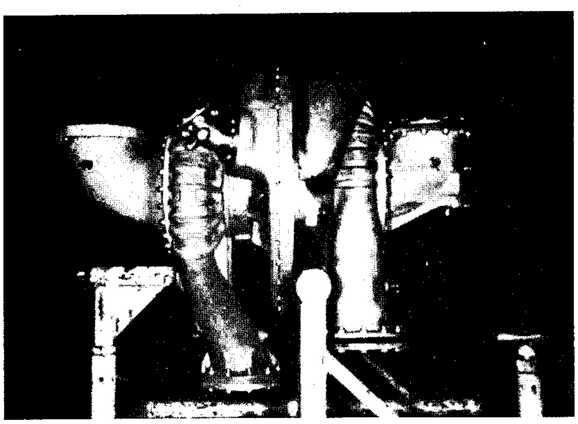

FIGURE IV–13.—Single-shaft turbopump for 700,000-lb.-thrust engine.

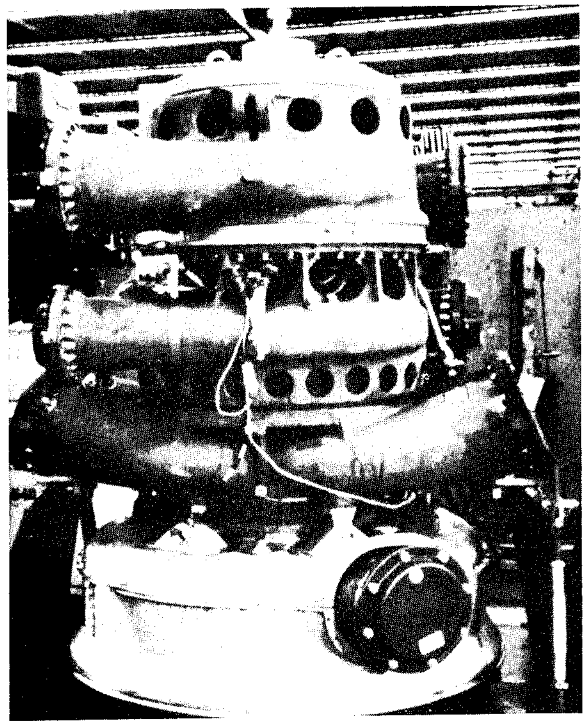

FIGURE IV–14.—Turbopump for 1500K-thrust engine.

TURBOPUMP DEVELOPMENTS APPLICABLE TO THE GENERAL ECONOMY

Items presented in this section have been developed in connection with turbopumps and may have some applicability to the general economy.

The turbopump, in configuration, is simply constituted. It is made up of two pumps and a single turbine variously mounted on a single shaft, or, in the past, a gear box has been used to transmit power from the turbine. Both roller and ball bearings that will take radial and axial loads imposed on the rotating assembly have been used. Dynamic seals are used at the impeller and on the shaft to control leakage

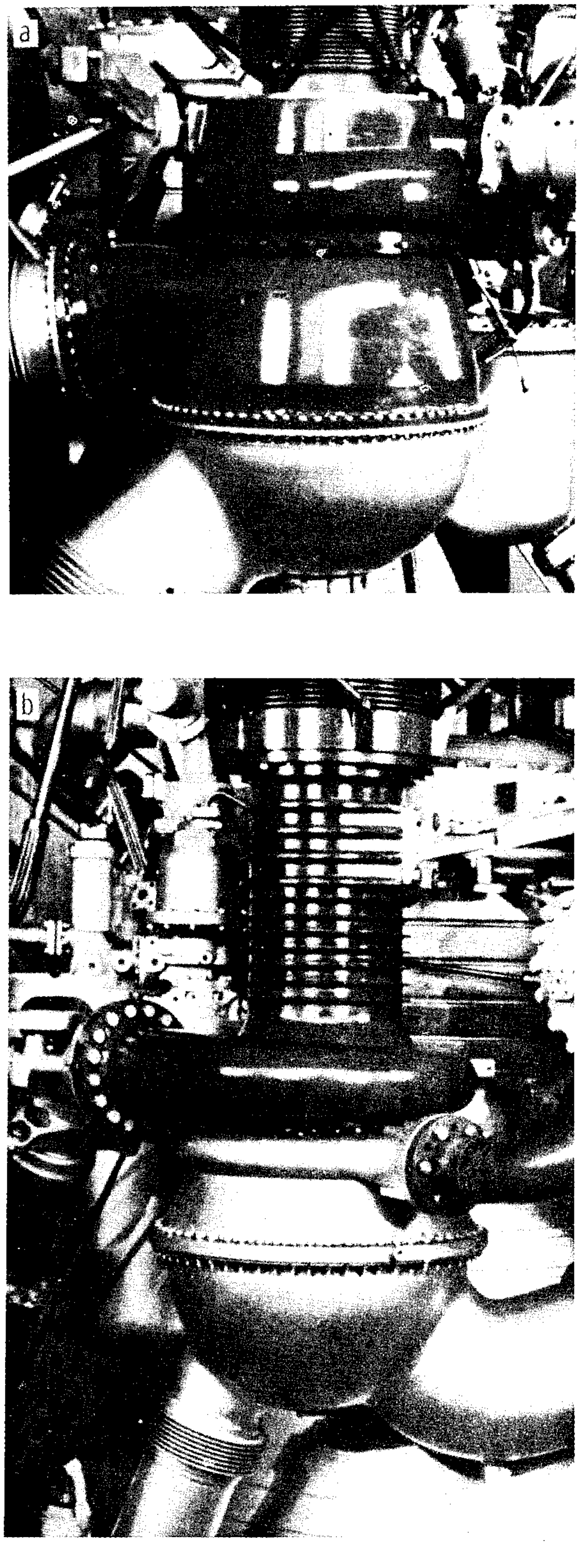

FIGURE IV-15.—Dual-shaft turbopumps for 200K-lb.-thrust engine.

and thrust, and are placed to prevent mixing of the propellants. Positive static seals are used in the stationary assembly to prevent the hazards of external leakage. The remaining major components are the pump volute, turbine manifold, and the shaft, the first of which must contain either high-pressure or high-temperature fluid within a sound structure, and the latter must transmit torque through spline or curvic couplings. These components will suffer and withstand deflections, temperature gradients, misalignments, etc.

Inducers

Figure IV–16 shows a cavitating-type inducer mounted on the shaft with the pump impeller. Under conditions of low-inlet net positive suction head, the inducer operates in a cavitating condition but provides a head rise sufficient to suppress cavitation in the main impeller, and thus permits it to work satisfactorily. High-speed pumps can, therefore, be operated at a much lower inlet head than conventional pumps, and the net gain is very much lighter and smaller turbomachinery. Figure IV–17 shows the weight reduction obtained by increased turbopump rotational speed. Most of

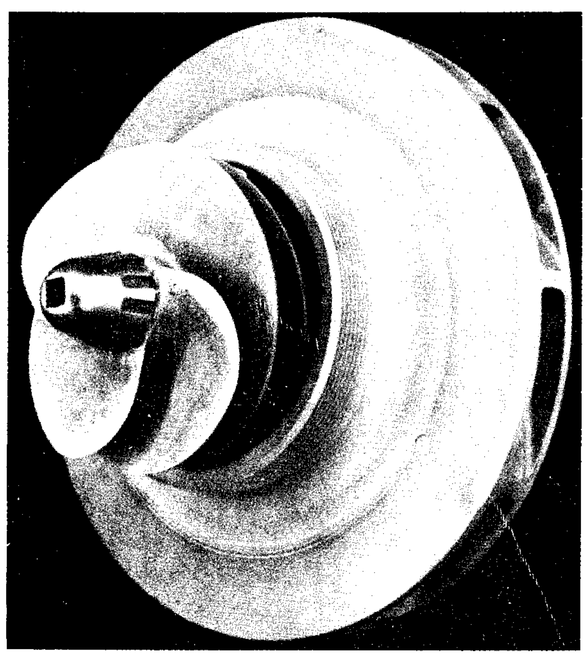

FIGURE IV-16.—Cavitating inducer and impeller.

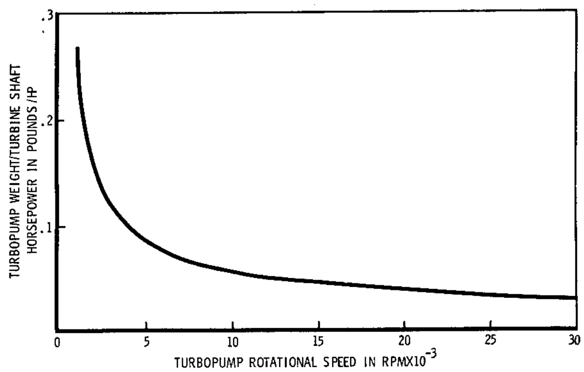

Figure IV–17.—Turbopump weight/turbine shaft horsepower versus turbopump rotational speed. The pump pressure rise is 2,000 psi and the pump flow rate is 10,000 gpm.

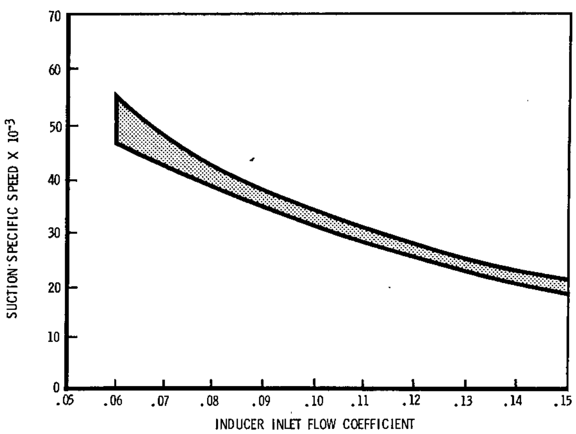

Figure IV–18.—Effect of flow coefficient on suction specific speed.

these gains have been made possible by improvements to the inducer. This weight-saving is critical in flight hardware and is also important for commercial machinery, because lower weight and smaller size often result in reduced costs. An important parameter for an inducer is the suction specific speed at which it is able to operate and develop head. The improvement in suction performance obtained by utilizing a low-flow-coefficient inducer is illustrated in figure IV–18. Conventional pumps are limited by head loss from cavitation to a suction specific speed of from 5000 to 8000, whereas rocket-engine pumps as a result of intensive development efforts over the years have been improved to 40,000 in water.

The important design parameters for an inducer giving approximately 35,000 suction specific speed in water are shown in table III.

It is important to note that cavitation performance is poorest in cold water and other liquids having similar thermodynamic properties. The described inducer will give in excess of 40,000 suction specific speed in liquids (such as liquid oxygen) that are being pumped near their boiling point. In liquid hydrogen, the suction specific speed attainable is over 70,000.

The blades of the inducer at design conditions operate under cavitating conditions, with consequent wear to the inducer and surrounding case. This is of only minor consideration in

Table III.—*Cavitating-Inducer Design Variables*

Variable	Typical value	Considerations
Inlet-blade angle	8 to 16 deg	Flow coefficient, angle of attack
Angle of attack	4 to 8 deg	Performance, flow coefficient, blade loading
Radius ratio	0.2 to 0.5	Performance, shaft critical speed
Blade length	1.5 to 2.0 solidity at tip	Desired solidity
Number of blades	3 to 5	Desired solidity
Hub contour	Cylindrical to 15-deg taper	Compatibility with impeller and shaft geometry
Tip contour	Cylindrical to 15-deg taper	Compatibility with impeller geometry
Blade loading	Leading edge—Channel	Performance
Leading edge	Swept forward, radial, swept back	Blade stress, performance
Sweep angle	Normal to shaft to 15-deg forward	Blade stress
Blade thickness	0.070 to 0.300 chord	Blade stress
Tip clearance	½ to 1 percent of tip diameter	Shaft axial and radial deflections

short-life rocket-engine pumps, but is a serious limitation in commercial pumps that require long-operating life. It has limited the application of these inducers, but prewhirl offers a possible means of alleviating this problem.

Prewhirl

A great deal of this cavitation can be suppressed and possibly eliminated if a technique known as prewhirl is used. Figure IV-19 illustrates the application of prewhirl to the inlet of a cavitating-inducer, centrifugal-pump combination. Prewhirl consists of bypassing a small quantity of high-pressure pump-discharge flow to the inducer inlet. This secondary flow of high-energy fluid swirls around the inlet pipe outside annulus and suppresses inducer backflow and cavitation. This is illustrated in figure IV–20. The first photograph indicates the inducer cavitating during normal pump operation. The second photo shows the same inducer with prewhirl in operation. Notice the great reduction in backflow and cavitation and the general smoothing of the flow. There is also a large reduction in pump-discharge pressure oscillations, as illustrated in figure IV–21. Prewhirl will, in addition, increase the suction specific speed of an inducer.

The prewhirl is in the direction of rotation and can thus reduce the Euler head of the pump.

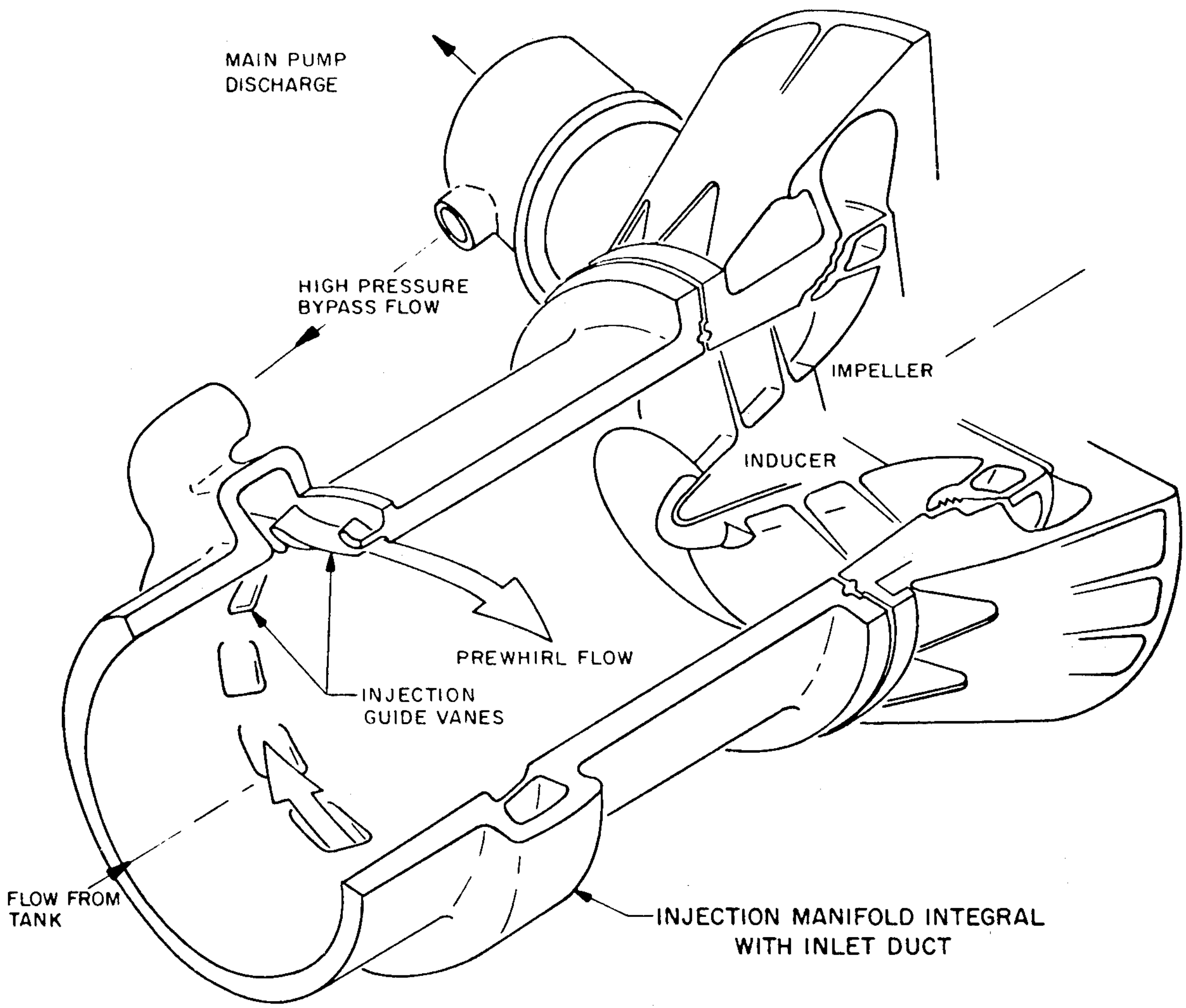

FIGURE IV-19.—Turbopump inlet fluid injection schematic.

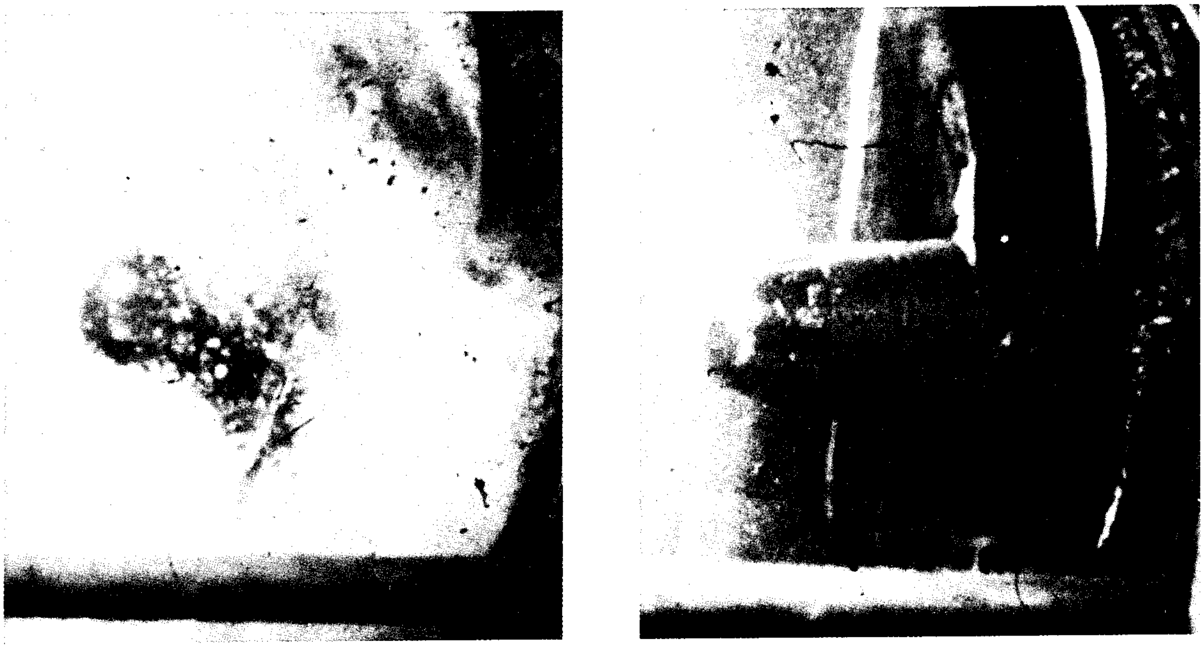

FIGURE IV-20.—Effect of prewhirl on inducer.

This is an aid in broadening the operating range, as the stall range can be extended and efficient operation achieved at low-flow conditions. Depending on requirements, from 2 to 15 percent of the pump flow is bypassed for prewhirl. Bypassing lower head fluid from the inducer discharge, rather than from the pump discharge, offers a means of reducing the loss associated with the process, because of the improved ejectory efficiency of lower-momentum bypass fluid.

Seals

A great deal of development work has been done on rocket-engine turbopump-shaft seals. While particular emphasis has been on cryo-

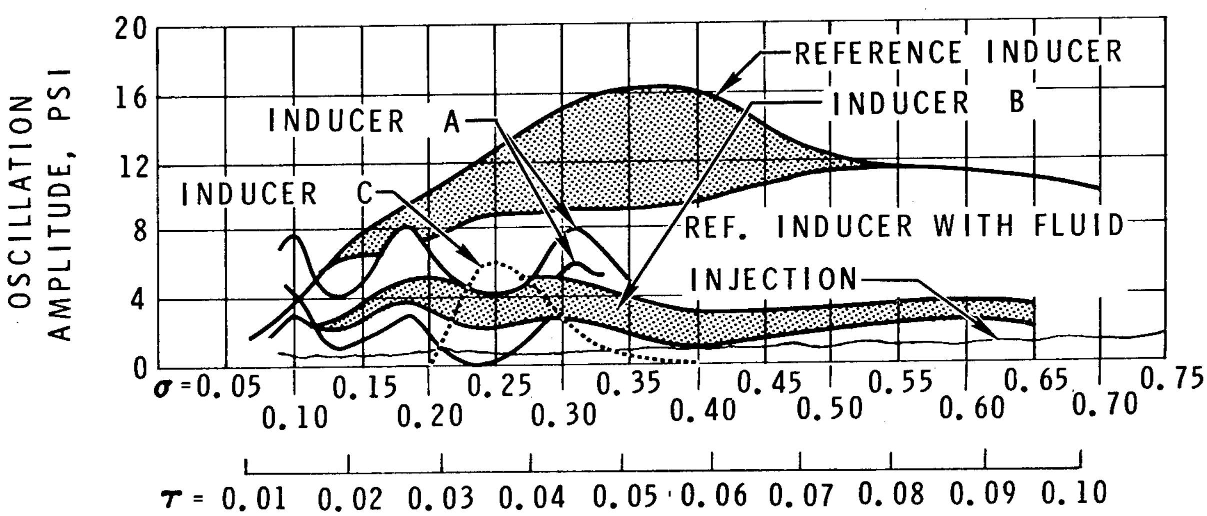

FIGURE IV-21.—Inducer oscillation reduction. Cavitation parameter $\sigma=\frac{NPSH}{\Delta H_N}$; $\tau=\frac{NPSH}{\frac{v_T^2}{2g}}$.

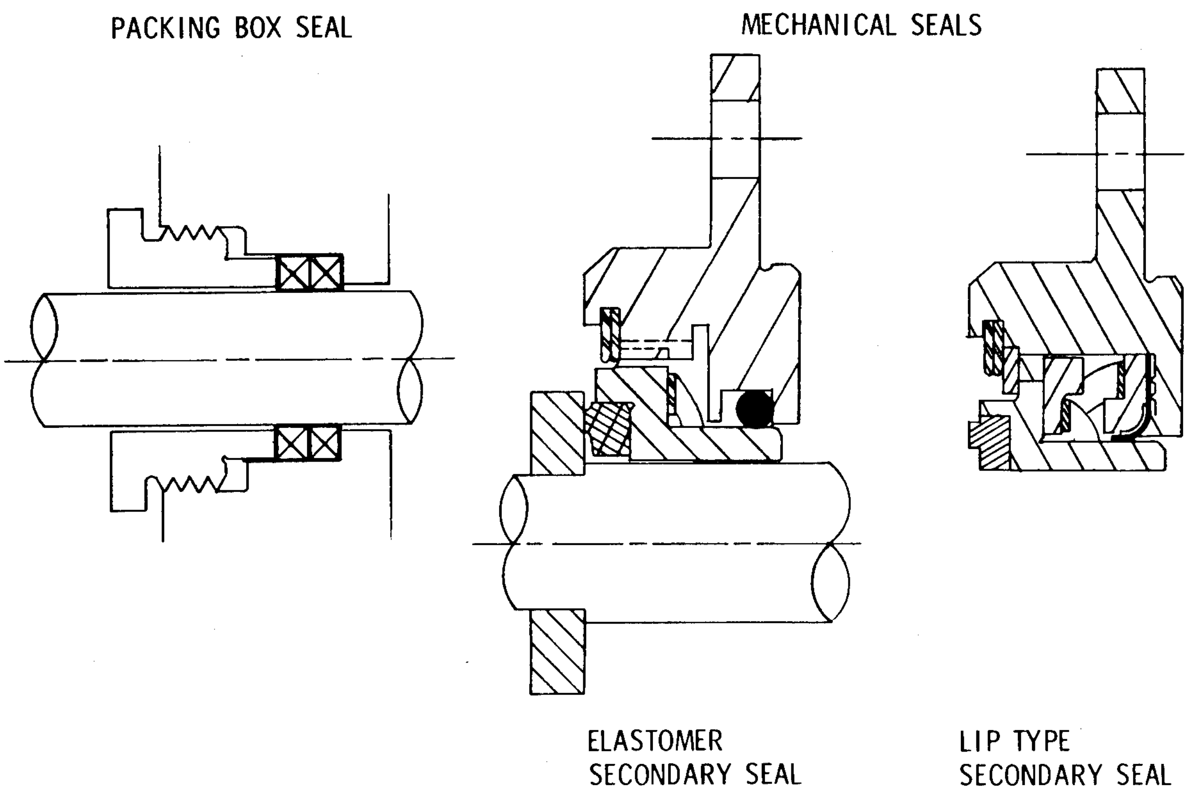

FIGURE IV-22.—Shaft seal types.

genics, the results are applicable to seals in other extreme environments. The basic seal types are shown in figure IV-22. In the past, commercial machinery has extensively used the packing-box seal. This seal always has some leakage, and historically has been a very troublesome device. The requirements of reduced leakage, higher shaft speeds, and improved reliability have resulted in the development of the mechanical seal. Normally, an elastomer, such as a rubber O-ring, has been used on the secondary seal that seals along the path of the axial movement of the nosepiece carrier. Severe operating regimes of both very low and very high temperatures have led to the development of a lip-type secondary seal for rocket-engine applications.

Dynamic shaft-seal developments during the past two or three years have pointed out the advantages of using metal bellows-type face seals (see figure IV-23) for the severe applications of the aerospace industry. The extreme

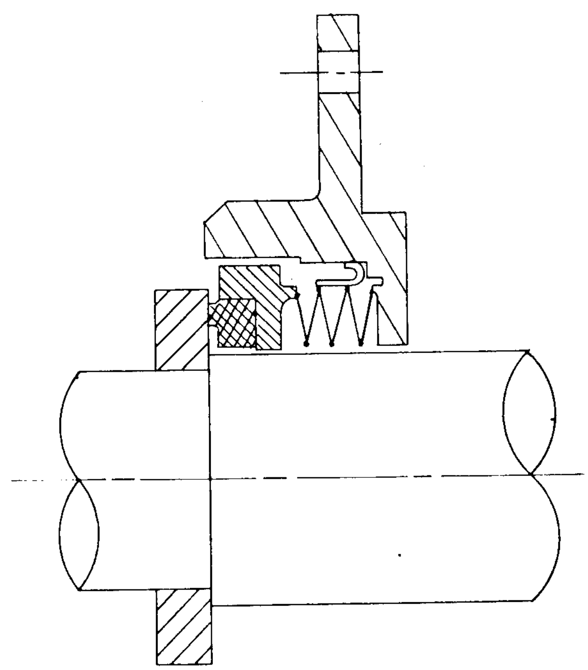

FIGURE IV-23.—Bellows seal.

temperature requirements, often from as low as $-423°$ F to as high as $1000°$ F, have directed most of the face-type-seal test effort toward the bellows. The all-metal construction allows the seal to operate at temperatures that are limited only by the capability of the metal.

A properly designed bellows seal is capable of withstanding extremely high fluid pressure throughout large temperature ranges for long periods of time without the worry of elastomer deterioration and cure-date expiration. For this reason, the bellows-type seal has many potential applications for industrial usage. At the present time, the bellows seal is more expensive that the conventional elastomer type. However, as the rate of usage increases and the bellows are fabricated in volume, it is reasonable to expect that the costs may be comparable. Actually, when replacement costs are considered, the bellows seal may be less expensive in the long run, even at present prices.

Mechanical seals operating in a lubricating medium, such as oil, can have practically no leakage. Such is not the case, however, when sealing a nonlubricant, like gaseous nitrogen. In this case, the leakage rates can have an acceptably low value of 6 scim of gas-sealing against 30-lb pressure, at 8000 fpm seal-surface speed for a 2-inch-diam. seal.

High-Load, High-Speed Bearings

Experimental investigations conducted for space development programs have been effective in breaking down barriers and extending previously accepted limitations of speed, loading, and cooling of the rolling contact bearings.

Prior to 1955, 1,000,000 DN (bore in millimeters multiplied by speed in rpm) was considered to be extremely fast for ball and roller bearings. Because of the advances in bearing geometry and lubrication techniques required for turbomachinery applications, bearings operating at 1,500,000 DN are now fairly commonplace, and have proved to be reliable. It was found, for instance, that highly loaded roller bearings equipped with inner-land riding cages are quite difficult to lubricate properly at altitudes of 100,000 feet and more. Similar bearings equipped with outer-land riding cages, providing easy lubricant entry, experienced no difficulty under vacuum environments.

It has been found that the maximum compressive stress existing between races and rolling elements can be extended almost to the plastic flow range if proper lubrication techniques are employed. It is paramount to maintain a heat balance in which heat is removed from the bearing at the rate it is generated, at a temperature low enough to maintain proper materials properties.

Nonconventional Lubricants

Bearings may be made to accept high loads and speeds with proper lubrication by conventional lubricants, such as oils. However, an advantage can be obtained by using process fluid as the bearing coolant/lubricant. Experimental investigations have shown that with proper material selection, such fluids as RP–1, LH_2, N_2O_4, IRFNA, and LO_2 can cool high-speed (1,000,000 DN) ball bearings.

In another investigation, it was shown that by careful attention to detail design of ball bearings, the operating speeds and loads can be extended using coolants with little or no lubricity. A ball bearing cooled by LH_2 has been operated for short periods at speeds to 4,000,000 DN, and for useful durations at 3,000,000 DN.

In summary, it might be stated that experimental programs aimed at development of rocket-engine turbomachinery have freed users of rolling contact bearings from some of the limitations in speed, load, and lubricants formerly accepted by industry in general.

Recent Advances in Mechanical Gearing Transmissions

Between 1958 and 1964, there has been a slow but steady advancement in the load-carrying capacity of aerospace and rocket-engine gearing. There have been no major breakthroughs, but the combination of empirical metallurgy and better quality control has resulted in gearing with 1½ to 2 times its previous load-carrying ability.

Quality assurance begins with the rigid control of the alloy composition and is almost continuous during the pouring, forging, cutting, and heat-treating operations.

Most of the material for aerospace gears is produced by the double-vacuum melted process, using consumable electrodes. Extreme cleanliness is a must, and carbon content of the alloy is controlled in some instances within .02 percent.

Heat-treatment cycles are specified and then rigidly controlled. Parts are stress-relieved in dual cycles of +300° to −100° F. The latest carburizing furnaces are of the stainless-steel-retort type, with infrared analysis and control of the carburizing atmosphere.

Sample slugs and sample parts are subjected to exactly the same heat-treating process as the production parts are. The samples must be acceptable by metallurgical evaluation before the parts are purchased. Sample parts are then run at conditions equal to or greater than actual operating conditions. Failure of a manufacturer's parts to pass these qualification tests means disqualification of the manufacturer as a supplier.

Improvements in the accuracy of measuring devices have made it possible to tighten tolerances and still maintain the ability to measure repeatedly.

Ten years ago, some manufacturers talked in terms of .0001 inch and were able to measure to from .0002 to .0005 inch. Today, the same people talk in terms of millionths of an inch and measure repeatedly in a range of .0001 to .00005 inch and as low as 5 microinches.

To accomplish this, the measuring instruments and parts are kept in so-called white rooms, where temperature, humidity, and dirt levels are rigidly controlled.

Surface finishes are now measured as to finish, lay, and waviness. It has been found that these factors have a great influence on scoring resistance of the gear surface.

Shot-peening of gears, used in the past as a corrective measure, is now part of the original design to induce beneficial compressive stresses and relieve discontinuities in gear roots, webs, and rims. Increases of up to 50-percent improvements in fatigue life have been obtained in some instances. The same peening procedures are used on splines and couplings, with similar results.

Improvements have been made in design theory. Profile modifications used to be a matter of experience.

Today, detailed profile measurements, deflections, and calculations are made all along the line of action. Entire profile modifications are calculated before a gear is run, thus decreasing scoring, finding, and compressive failures.

Root stresses are now calculated with much greater accuracy, and loads of 1½ to 2 times those of a few years ago are being used. Unit loads of 40,000 to 45,000 and bending stresses of 80,000 psi are common practice for life cycles up to 10,000,000. An index of the compressive strength of a gear is the K factor. Production gears are running today with K values of over 2000, whereas K values of 900 used to be considered as high. Metallurgy and a dimensional accuracy have been the most important contributing factors.

Ten years ago, a pitch-line velocity of 20,000 ft/min was considered a maximum to prevent scoring failures. Today, the ability to control gear-face surface conditions more accurately and the use of lubricant additives have relieved the scoring problem to the extent that pitch-line velocities of 50,000 ft/min are obtainable.

The greatest area of improvement occurred in lubrication of aerospace gearing. For example, kerosene by itself can carry only 500 lb/in. of face loading. By the addition of 3 percent by volume of extreme pressure additives, load-carrying capacity of over 6000 lb/in. of face has been demonstrated.

TABLE IV.—*Comparing Compositions of Aluminum Alloys 356 and Tens–50*

Elements	356	Tens–50
Si	6.5–7.5	7.6–8.6
Mg	0.25–0.40	0.40–0.55
Be		0.15–0.30
Ti	0.20 Max	0.10–0.20
Fe	0.13–0.30	0.30 Max
Cu	0.10 Max	0.10 Max
Mn	0.50 Max	0.20 Max
Zn	0.05 Max	0.20 Max
Al	Remainder	Remainder

Gears pretested with an extreme-pressure film of millionths-of-an-inch thickness can later be operated in kerosene only at loads up to 4000 lb/in. It appears it may be feasible to pretreat gears and bearings with extreme-pressure films before putting them in actual service and then run them in any reasonable coolant.

This theory has been demonstrated under controlled laboratory conditions. However, additional research must be done before it can be applied to commercial transmissions. The use of dry-film lubricants is more prevalent and offers a potential future, especially for splines.

Special nitrited surface gears have been run at extremely high temperatures (600° F), and bearings and couplings have been operated at −300° and −420° F in gases and liquids of pure oxygen and hydrogen. Loads have not

TABLE V.—*Metallurgical Evaluations of Test Bars From Tens 50–T60 Aluminum-Alloy Sand Casting*

Location	Grade	Number of bars	Ultimate—psi	Yield—psi	Elongation—%
Leading Edge—Tongue 1	Critical	3	45, 000	36, 600	3. 7
Leading Edge—Tongue 2	Critical	3	49, 400	35, 300	7. 0
Leading Edge—Splitter 1	Critical	3	49, 800	38, 100	8. 5
Leading Edge—Splitter 2	Critical	3	47, 800	37, 500	6. 3
Center of Splitters	Standard	6	43, 000	35, 800	3. 0
Trailing Edge—Splitter 1	Critical	2	48, 600	36, 200	7. 5
Trailing Edge—Splitter 2	Critical	2	48, 100	36, 400	6. 3
Volute Walls	Standard	4	46, 800	36, 000	5. 5
Outlets	Non-Critical	4	45, 000	35, 700	4. 5
Inlet cylinder	Non-Critical	6	47, 200	35, 900	5. 9
Back plate	Non-Critical	3	43, 900	34, 800	3. 2
Bird Cage	Non-Critical	6	41, 300	34, 100	2. 7

Minimum specification requirements			
Grade of quality	Ultimate—psi	Yield—psi	Elongation—%
Critical	38, 000	30, 000	3. 0
Standard	36, 000	28, 000	2. 0
Non-critical	34, 000	26, 000	1. 0

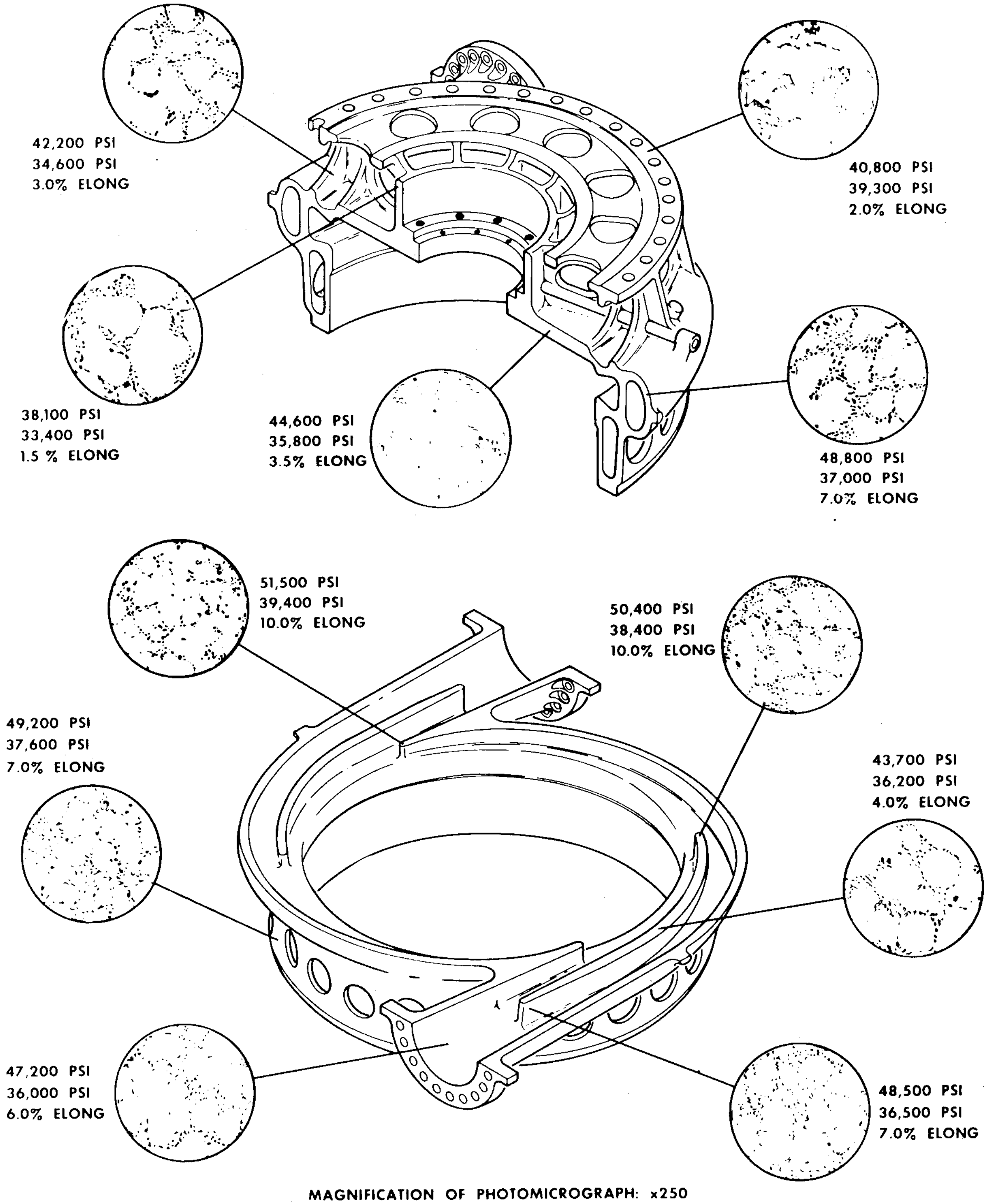

FIGURE IV-24.—Photomicrographic study and mechanical properties of F-1 fuel volute Tens 50-T60 aluminum-alloy sand casting. Weight of casting: 400 pounds.

been extremely high on gears, but the gears can carry significant loads (500 to 1000 lb/in.) for short times.

Present gears can carry approximately 40 hp for every pound of gear box and with a reliability of as high as .9996.

It is felt that the procedures, controls, and experience described could be applied to everyday industrial applications, resulting in lighter, more efficient, more reliable industrial products.

Development of Aluminum-Alloy Castings

In the early 1950's, design values for ultimate strength and yield strength of castable aluminum alloys were approximately 23,000 and 15,000 psi, respectively. As a result of considerable research-and-development work in the aerospace industries in recent years, one can now confidently use values of over 45,000 psi ultimate and 36,000 yield.

One of the most widely used general-purpose, castable aluminum alloys has been 356–T6. Imparities like iron, however, limit the heat-treatability of the 356 alloy. The iron forms needle-shaped crystals that are brittle, and therefore it is not possible to heat-treat the alloy fully without serious damage to ductility.

The alloy Tens–50, developed at Rocketdyne, overcame this defect in 356 by modifying the shape of the brittle iron crystals to harmless modules, through a beryllium addition. A further improvement was also made by increasing the heat-treatable hardening constituents (magnesium and silicon), resulting in a higher heat-treatable strength. The compositions of 356 and of Tens–50 are compared in table IV.

Successful results in minimizing casting porosity due to gas or shrinkage have been achieved by the combined effect of controlled melting techniques and extensive use of chills in the mold design.

Normal melting precautions, such as control of purity of furnace charges, proper degassing procedures, and controlled holding and pouring temperatures, are important in the production of porosity-free aluminum castings.

Statistical analysis shows, however, that these precautions do not guarantee consistently sound castings. When good melting and pouring techniques are combined with the extensive use of Leary chills in the mold design, a real improvement is achieved, because of the extremely rapid solidification.

As an example of the properties achieved in an actual casting, a Tens 50–T60 aluminum-alloy sand casting of a turbopump volute was metallurgically analyzed. This test is part of the routine metallurgical evaluations that are performed on all Rocketdyne castings. Fifty-two round (.250-inch-diam.) test bars were machined from the casting. Table V shows the results. Ultimate strength as high as 49,800 psi, yield strength as high as 38,100 psi, and elongations of a maximum of 8.5 percent were obtained. Individual test bars machined from the most significant areas of the casting were analyzed microscopically, and the results are shown in figure IV–24.

V. Some Questions on the Economics of Technological Transformation

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Any consideration of the economics of technological transformation from a space-oriented to a civil, Earth-oriented industry must be predicated on certain underlying assumptions. Perhaps the most important of these is that, in the first place, the national economy justifies the space program. This implies that we, as a nation, have agreed to allocate a certain percentage of our resources to achieve some defined objectives in space. Such a social decision, in turn, is based on some assessment of how much it will cost us as a nation to meet these objectives. On the other hand, it should be apparent that, to the extent that other than space-program benefits may derive from the space program, some allocation of costs may be charged to them. However, since the primary objective is the space program, such allocations must perforce be considered as incidental.

Secondly, we must assume that there are developments which are occurring in the space program that are significant to our non-space economy. The problem then becomes one of identifying these contributions to the non-space economy, establishing some reasonable basis for their cost allocation. The purpose of this paper is to raise questions germane to this problem, rather than to provide answers.

ECONOMICS OF THE SPACE PROGRAM

The money expended on the space program may be looked upon as a capital investment. Like any capital investment, large initial sums are expended in anticipation of some later return with profit. Whereas we can measure the costs as we incur them, the return of the investment with profit is uncertain. The degree of uncertainty depends both on the futurity of the return and on its degree of predictability. As a consequence, the higher the risk and the greater the futurity, the higher will be the expected return that we must demand in order to justify the investment. The space program is like any other investment in this regard. Perhaps one difference is the highly subjective social belief that there will be a payoff. One of the very important questions that may be asked is what is the true magnitude of the space investment. Present-day accounting practices tend to confuse the assessment of the investment by charging all costs as direct. Because of this, we conceal the true capital nature of the investment. In particular, possibly the most significant capital investment we are making, and for which a payoff may be expected both for later stages of the space program and for many other things that are independent of space, is the gain in knowledge of the people associated with the space program. This notion of a hidden capital in men is not new. Many economists, such as Prof. Schultz of Chicago, and others, have called attention to it. In fact, it has been suggested that it is this component of our national capital investment that may contribute most significantly to the growth of our economy.

On one hand we may recognize the nature of this capital, but on the other we must admit that an investment in capital does not, by itself, guarantee a return. Consequently, one must properly question how the return on this space-generated human capital is to be realized.

Perhaps the largest single component of expenditure in the space program comprises the salaries paid to men to study and to learn new technologies and new skills in order to be able to solve the problems confronting them. Whenever a technology is pushing a state of the art, it takes a lot of time for the men to acquire the knowledge needed to move ahead. Thus, while the space program may seem expensive, it is partly because of this fact. The acquisition of this new knowledge may still promise a return if it is applied to other than space problems. If, for example, it turned out to be in the public interest to cut back the space program, the people who would be compelled to transfer out of the industry would be in a position to apply their new knowledge to other problems of concern to society. Hence, the return on the capital invested in them as a consequence of the space program would consist of a payoff in the new activity. Of course, I do not wish to suggest that space is an activity that will diminish. It probably will continue to grow, with the result that the payoff in new learning will reflect in continuing accomplishment and diminishing cost.

While I contend that a transfer from space is not necessarily a loss, at the same time I must admit that there is some loss of capital value when men transfer from one activity to another. Unfortunately, this has always been all too true in the aerospace and defense segments of our economy. The shifting of people from one company to another company, with the concomitant loss of effectiveness, has been done with too little recognition of capital losses incurred.

While the foregoing comments imply that much of the capital investment currently being made in the space program could be allocable to other things, we must still come back to the point that investment in space must be made on the basis of its own justification. Any derived benefits for other segments of our economy must be considered as incidental. It is important that we identify what these are and have some idea of their magnitude.

ECONOMICS OF SPIN-OFF

This brings us to the question of the economics of the development of space-derived new technologies in the non-space segment of our economy. To start with, it is self-evident that the costs of producing new products, even when we charge all of the capital, which is permissible, to the space effort, must be less than the income that we expect to derive from their sale. If we consider that the capital investment in new knowledge would be free capital for new product lines, it may still not prove economical to develop them. There is no assurance that just because something is free it has an economic value. There are many situations, which we could exemplify, in which companies or industries or even individuals have attempted to use a resource because it was free, when in reality it might have been more economical to make an entirely new investment, with a considerably greater expenditure. If we apply this to the capital investment in the people who have been trained in the space industry, we might very well find that the retraining or reorientation to a non-space industry is simply not justified in terms of any payoff to the industry. This is not to say that such further investment by society is not justified in relation to the larger economics of the entire society. From a single industry viewpoint, it might very well prove to be more economical to develop the knowledge of the people within that industry from the start, as if there never had been a space program. In other words, it might prove to be that new knowledge acquired in a space program is transferable to non-space programs only to a very limited degree.

Another factor involved in the utilization of the human capital of the space program is the ability of the non-space industry to take advantage of it. Characteristically, there are a great many more people involved in the engineering functions associated with space than there are in the non-space industry.

Therefore, the technical competence may be lacking in the non-space industry to absorb significantly large contributions from the space industry. In order for the non-space industry to take advantage of new technology, it may first have to involve its present people in extensive retraining and reorientation programs.

One further problem must be realized. Private industry, in developing consumer products, necessarily has different attitudes toward risk. The space industry, by its very nature, is a high-risk industry. However, the mechanism for financing the space program involves shifting of the risk to Government, with the result that the companies involved in space programs are not risk-oriented. A non-space industry may be more risk-oriented but, nevertheless, in developing a consumer product will proceed slowly in order to insure that each level of commitment promises a reasonable expectation of return in the long run. Therefore, it must limit its risk. Thus it takes a long time for market surveys to be made for identification of needs, for planning of production, and for careful assessment of price in relation to market factors, as well as for all of the other questions that must be taken into account before a new product is ready to market. The consequence of this is that even where new technologies are potentially feasible, it may be a long time before we will see them manifested in new products.

Size of a new program is something that must be taken into account in considering the economics of transformation. There are undoubtedly many potential new products that may be developed economically by small companies. However, it is often the small company that lacks the resources, or recognizes that the risk associated with the development is too great in relation to its size, to take the initiative. At the other extreme, there are large programs that are economical derivatives of the space program but are too comprehensive and too large for any single company to undertake by itself. Perhaps the best example of this we have is the communication-satellite program. The methods for accomplishing this program speak for themselves.

GOVERNMENT POLICY

The implications of these remarks are that returns may be realized from the space program and that certain economies are possible. However, it is also implied that Government has a role to play if maximum benefit is to result. The Government, of course, represents society and, as such, should create an environment in which people individually will act to maximize returns. In this connection, I wish to make two points. First, society has an important stake in the investment and knowledge of the people employed in the space industry. Any shift in emphasis in the space industry must necessarily be accompanied by Government action to effect transference of these people to non-space industry, in order to utilize this resource for a social benefit.

Second, programs that involve excessive risks for private industry may not be excessive for the nation as a whole. Some mechanism must be found to absorb at least part of the risk by the whole society, in order that the remaining risk may represent attractive investment opportunities for private capital. This is, in effect, what was accomplished in the first instance with the space program. Space, as an undertaking, was far too risky for private industry to have undertaken on its own, but it was not too risky for society to do. As a result, we now have the potential for worldwide communication by satellite that is owned by private enterprise. Possibly one solution for this risk problem of technological transfer would be the development of some new form of insurance. We might call it Innovation Investment Insurance, and it could be underwritten by the Federal Government through an agency that we might call the Innovation Investment Insurance Corporation. The purpose of this agency would be to insure private industry—perhaps with special consideration to small industry—against excessive losses that might be incurred under a new technological investment. Such a program could be set up on a self-liquidating basis, in which the insurance premiums charged would be sufficiently high to offset losses from unsuccessful programs. Such a mechanism might even

provide a means for indirect subsidy for a limited number of programs demonstrated to be in the national interest.

There are certain things that I think are important to keep in mind—certain things that are inevitable, whatever the nature of technological transfer, to the extent that it may not prove feasible. I believe we might all agree that there will have to remain a continuing high level of scientific activity. Either this will manifest itself in a growing and expanding space age, with ever more challenging technological problems, or the space program will give way in part to some new type of technology that will evolve a national focus. Such new and changed technology may have to provide us with as much romance and drama as the space program has done before it. Perhaps it will be oceanography. Perhaps it will be a problem, such as surface transportation, more closely related to our everyday living on Earth. The alternative of not maintaining an expanding and high-level technology can only be economic collapse. That is our challenge. That is the challenge of technological transformation.

VI. Biochemical Energy Conversion Employing Human Waste as a Fuel

GEORGE E. ELLIS

The Marquardt Corporation

The Marquardt Corporation, Astro Division, of Van Nuys, California, is currently engaged in conducting research on biochemical fuel cells under a contract with the National Aeronautics and Space Administration.

The general goal of the program is to conduct empirical studies on biochemical fuel cells for degrading human wastes. Specifically, the study includes the evaluation of electrodes, electrolytes, separator materials, structural materials, adaptation of control and regulating devices, and the determination of storage and performance characteristics.

This contract is part of a three-phase program with two other firms. Personnel at one research laboratory are engaged in research in fundamental bioelectrochemistry, to determine the biochemical-reaction mechanism for producing electrical power via bacteria and enzyme action, and the methods of utilizing these reactions within a biological fuel cell. Research at another laboratory is being conducted in applied bioelectrochemistry, to determine the microorganisms and enzymes that might be applicable to degradation of human waste in the biochemical fuel cell, and simultaneously produce electrical power. The research at Marquardt stresses the developmental aspects of the biochemical fuel cell.

BIOCHEMISTRY OF THE BIOFUEL CELL EMPLOYING HUMAN WASTE

The exact composition of human feces is unknown. It has been stated that feces is composed of about 66-percent water, and only approximately 84-percent of the total feces has been even partially identified. Generally, the chemical components of human feces include fats, proteins, carbohydrates, minerals, vitamins, and pigments, in varying amounts. Bacteria, mostly nonpathogenic, compose about one-third of the dry weight of feces under average dietary conditions. The chemical composition of microorganisms includes a variety of proteins (refs. 1, 2 and 3). The average output of feces is 150 grams per man per day, but both the composition and amount of feces vary, depending upon the diet and physical condition of the individual from whom they are obtained.

Human urine consists mostly of water (95–99 percent); approximately 50 percent of the solids is urea and 25 percent is sodium chloride. There are also small amounts of nitrogen and protein, amino acids, carbohydrates, fats, derivatives of the above, vitamins, enzymes, and pigments. The urine output depends upon the water intake, external temperature, diet, and mental and physical state of the individual. It varies from 0.6 to 2.5 liters per day (ref. 4).

In the biochemical fuel cell, microorganisms oxidize higher energy components of the human waste (e.g., carbohydrates, lipides, proteins) to lower energy forms.

The electrochemical potential of the biochemical fuel cell changes as a result of the bacterial growth and metabolic reactions. At the same time, biochemical reactions probably are a result of the electrochemical activity (potential and current). Other variables affecting the bioelectrochemical activity include pH, temperature, accumulation of products and

depletion of reactants (nutrients), and type of environment (aerobic or anaerobic). The biochemical reactions may be rate-determining (i.e., slower than the electrochemical reactions) in the biochemical fuel cell.

OTHER RESEARCH ON BIOCHEMICAL FUEL CELLS

Not all of the biochemical fuel cells employ human waste as the fuel, as in this paper. Some of the other fuels used have included mushrooms (ref. 5), glucose and yeast, animal waste, and even grain hulls. Various enzyme systems have been used in biochemical fuel-cell studies, including oxidase, dehydrogenase, catalase, peroxidase, and esterase.

Potential applications of biochemical fuel cells include the generation of electrical power from industrial and agricultural wastes and sewage, small marine power sources operating on sea water, and unattended and portable power packages using industrial and agricultural wastes and sewage, in addition to the space applications described in this paper.

EXPERIMENTAL FUEL CELLS

A fuel cell differs from a battery, because the anode is not consumed during reaction. A biochemical fuel cell is further categorized by the metabolic reactions of microorganisms, either directly at the electrode or by producing products that may be electrochemically active.

A biochemical fuel cell is shown schematically in figure VI–1. The fuel to be oxidized is placed in the anode chamber and the oxidant in the cathode chamber. The two medial are separated by means of a semi-permeable membrane, which permits the interdiffusion of ions but prevents gross contamination of the anode and cathode media. Electrons are released from the anode as a result of oxidation of the fuel, and flow through the external circuit to the cathode. The circuit is completed internally by electrolytic conductivity, due to the migration of ions between the electrodes.

One of the types of experimental cells used in these studies is shown in figure VI–2. That cell is identified in this paper as an H-cell of

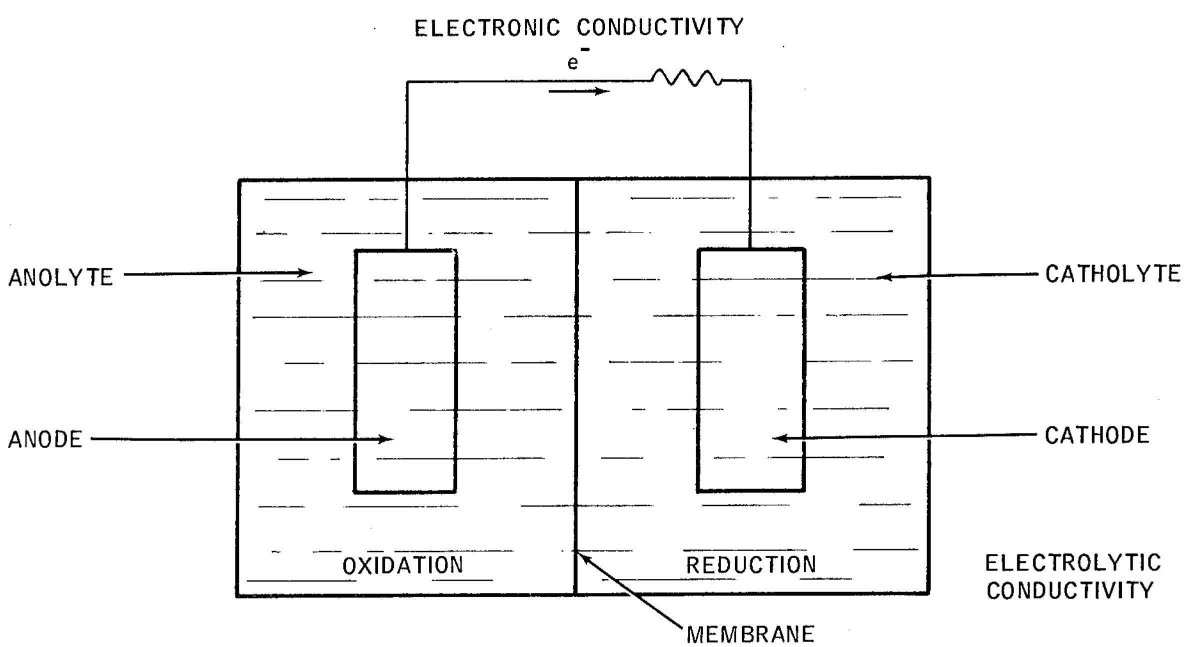

FIGURE VI–1.—Schematic drawing of a biomedical fuel cell.

Biochemical Reaction
- **Anode Chamber: Oxidizable Material (Fuel)$\rightarrow$Fuel$^+$+e^-**
- **Cathode Chamber: Reducible Material (*RM*)+$e^-$$\rightarrow$*RM*$^-$**
- **Overall Reaction: Fuel+Oxidant$\rightarrow$Products**

the agar-plug type. Both the anode and cathode chambers have a platinized platinum-foil electrode and a gas bubbler. Oxygen is bubbled into the cathode (nonbiological) chamber and helium into the anode chamber. The

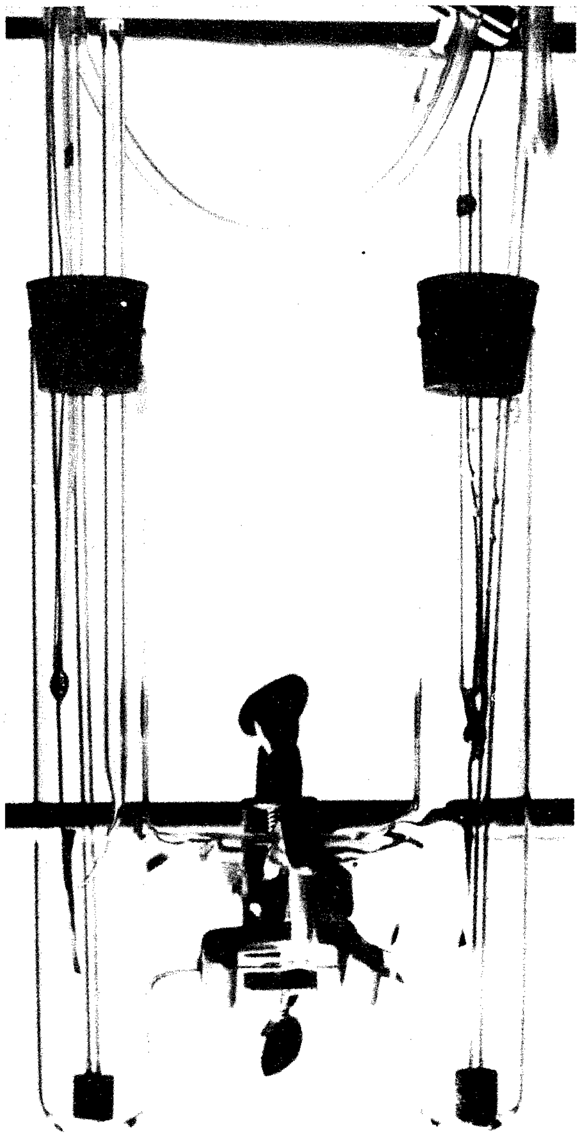

FIGURE VI-2.—Closeup of an H-cell of the agar-plug type.

anode chamber also contains a Luggin capillary, which provides an extension of the saturated potassium-chloride solution from the reference (saturated calomel) electrode to the proximity of the anode, and permits study of the anode half-cell. The anode and cathode chambers are separated by a fritted glass disc, against which an agar plug is embedded.

In a slight modification of this type of cell, O-ring joints permit the use of ion-exchange or dialysis membranes instead of the agar plug for separating the anode and cathode chambers.

A continuous-flow system, using a plastic cell, is shown in figure VI-3. The fuel-anolyte and -catholyte are pumped out of reservoirs, through the plastic cell, and returned to the reservoirs. The pumping action is accomplished by forcing the liquid through flexible plastic tubing (peristaltic action), so that the liquid does not contact any metal parts other than the electrodes. The reservoir provides space for the addition of microorganisms or nutrients, mixing, and bubbling with gases.

The plastic cell used in the continuous-flow system is approximately $3 \times 3 \times 2$ in. assembled, with 1¼ in. between electrodes. The effective diameter of the electrodes is approximately 2⅛ in. The electrodes are either platinized screen (90-percent Pt—10-percent Rh, 80 mesh, 0.003-in.-diam. wire) or platinized platinum foil.

TABLE I.—*Experimental Conditions, Biochemical Fuel Cell*

FLOW SYSTEM

CELL: Plastic.

SEPARATOR: Cellulose acetate (Sargent S–14825; 0.001-in. thick).

ELECTRODES: Platinized screen (90 percent Pt—10 percent Rh), 80-mesh, 0.003-in. dia. wire, 2⅛-in. clear diameter, 3.56-sq.-in. geometric area.

O-RINGS: Silicone (Dow Corning S–7180).

CATHOLYTE: 5 percent by weight NaCl-5 percent KCl in sterile, deionized water. Bubbled with oxygen. Nonbiological.

FUEL-ANOLYTE: 30 gms. nonsterile human feces (special diet; frozen and thawed) in 100-ml. nonsterile human urine (frozen and reheated to 120° F). Homogenized. Bubbled with helium.

NONFLOW SYSTEM

CELL: Glass, H-shape, O-ring type, nonflow.

ELECTRODES: Platinized Pt foil, 1-sq.-in. area (nonopposing faces coated with chemically resistant, water-repellent paint).

SEPARATOR, O-RINGS, CATHOLYTE, FUEL-ANOLYTE: Same as for flow system.

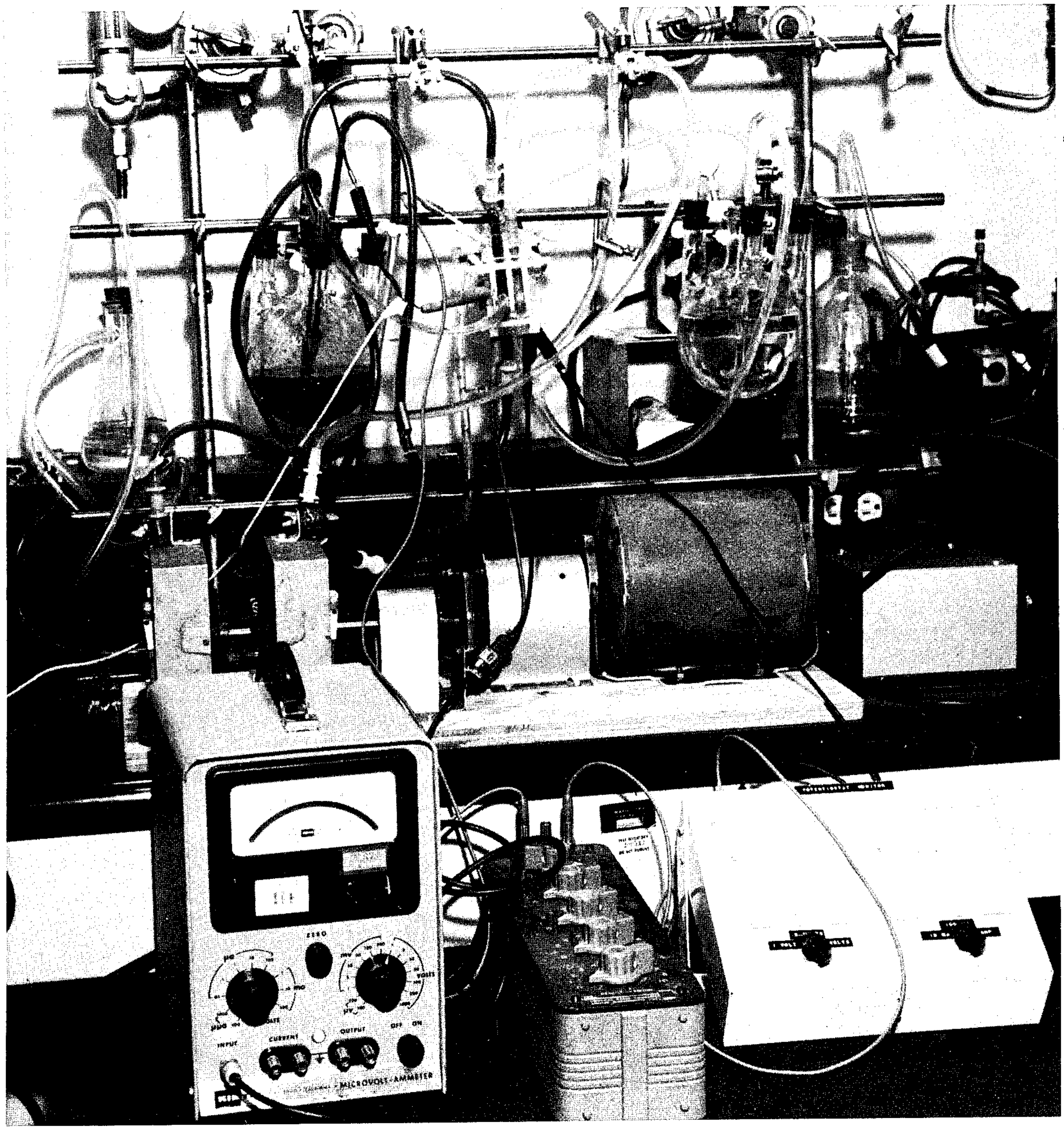

FIGURE VI–3.—Continuous-flow biofuel-cell system.

The experimental conditions for both the flow and nonflow systems are described in table I.

Open-circuit potentials are routinely obtained between the anode and saturated-calomel reference electrode, and between the anode and cathode. These values are printed every 30 minutes on tape by a 50-channel digital voltmeter.

A typical arrangement of cells connected to the digital voltmeter is shown in figure VI–4.

Polarization data (potential vs. current) are obtained with X–Y plotters and motor-driven resistance pots. The anodic values are obtained on one plotter and total cell values on another.

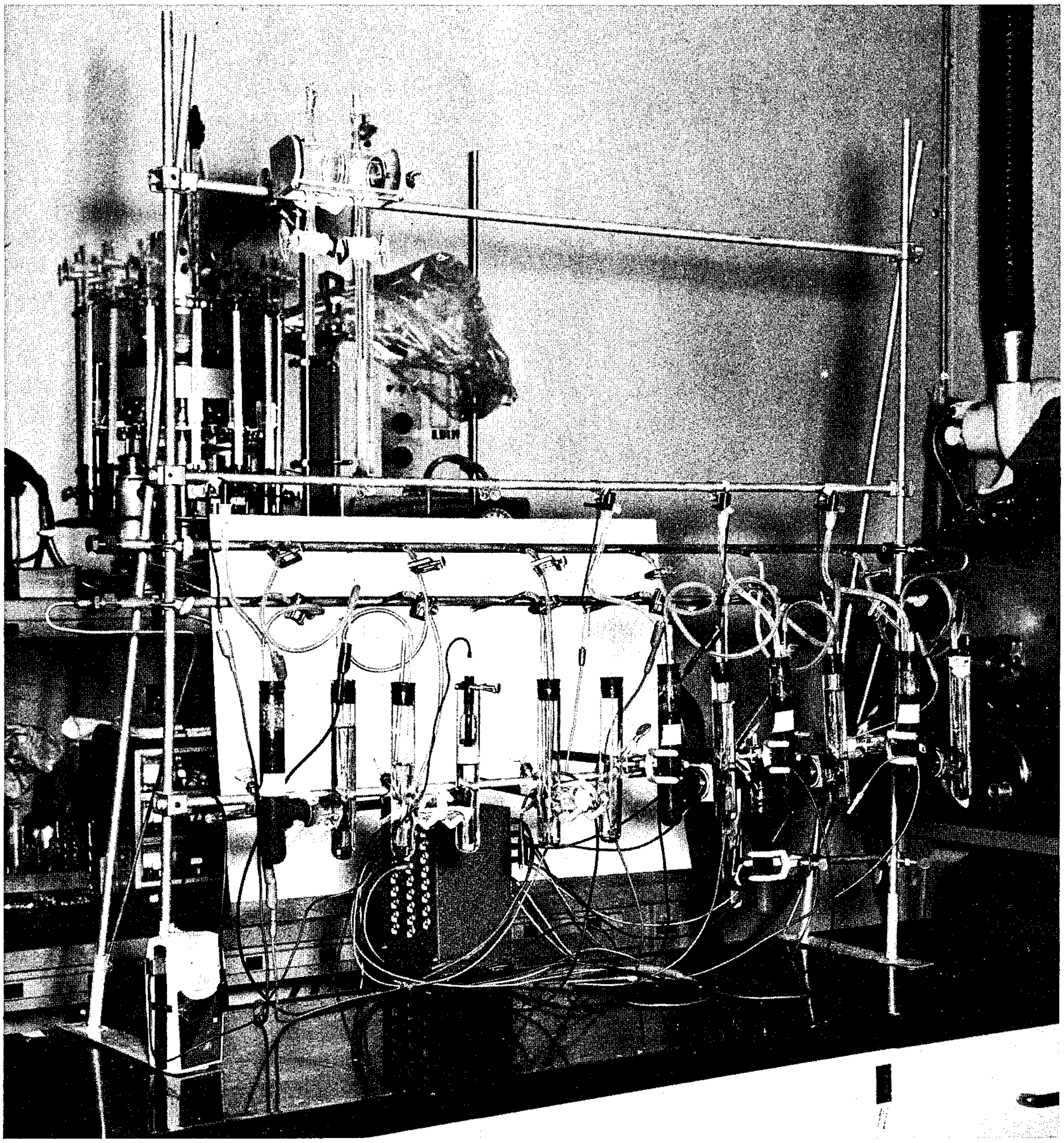

FIGURE VI-4.—Biochemical fuel cell of the nonflow type.

A typical anodic-polarization curve is shown in figure VI-5 and an anodic-power-density curve in figure VI-6.

Electrolytic resistivities of solutions and membranes are measured with a conductivity cell and impedance bridge.

EXPERIMENTS AND RESULTS

Human Waste as a Biofuel

Either human urine or human feces (nonsterile), or mixtures of urine and feces, have been employed as biofuels in these studies.

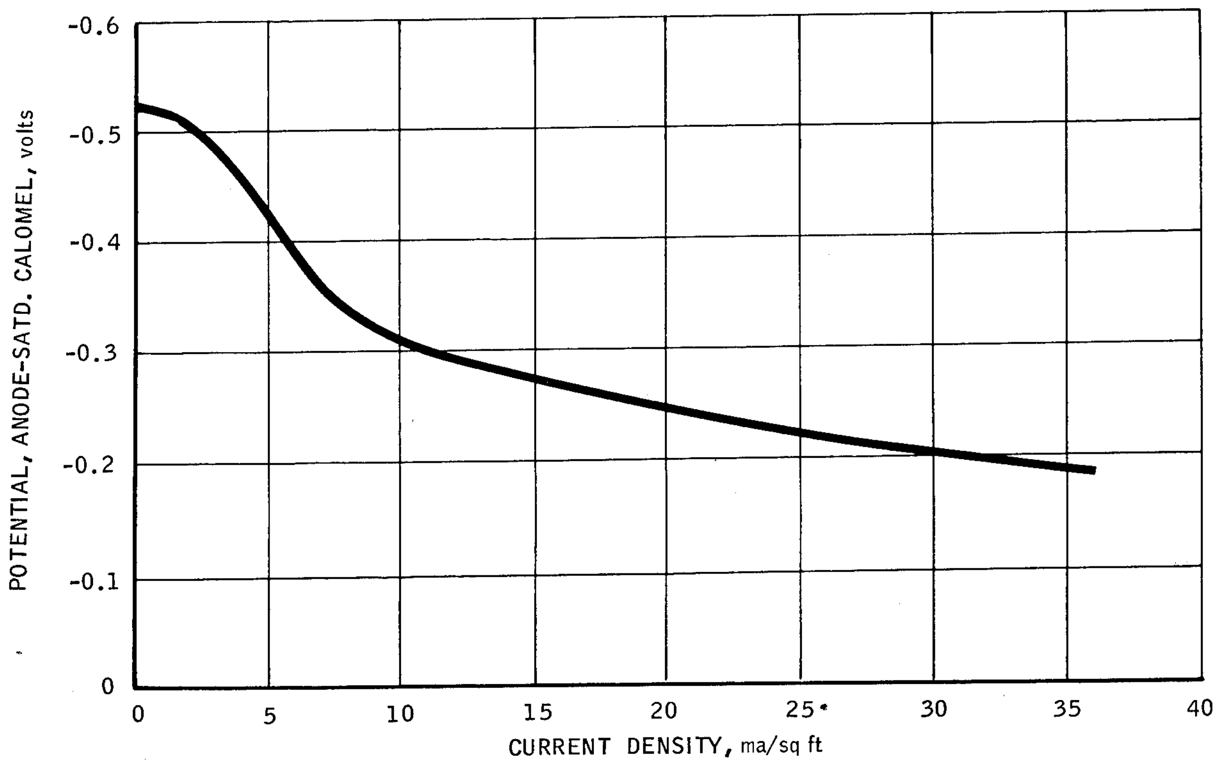

FIGURE VI-5.—A typical anodic-polarization curve. The cell is continuous flow, plastic; the pH is 8.3; and the temperature is 23° C. (System is described in table I.)

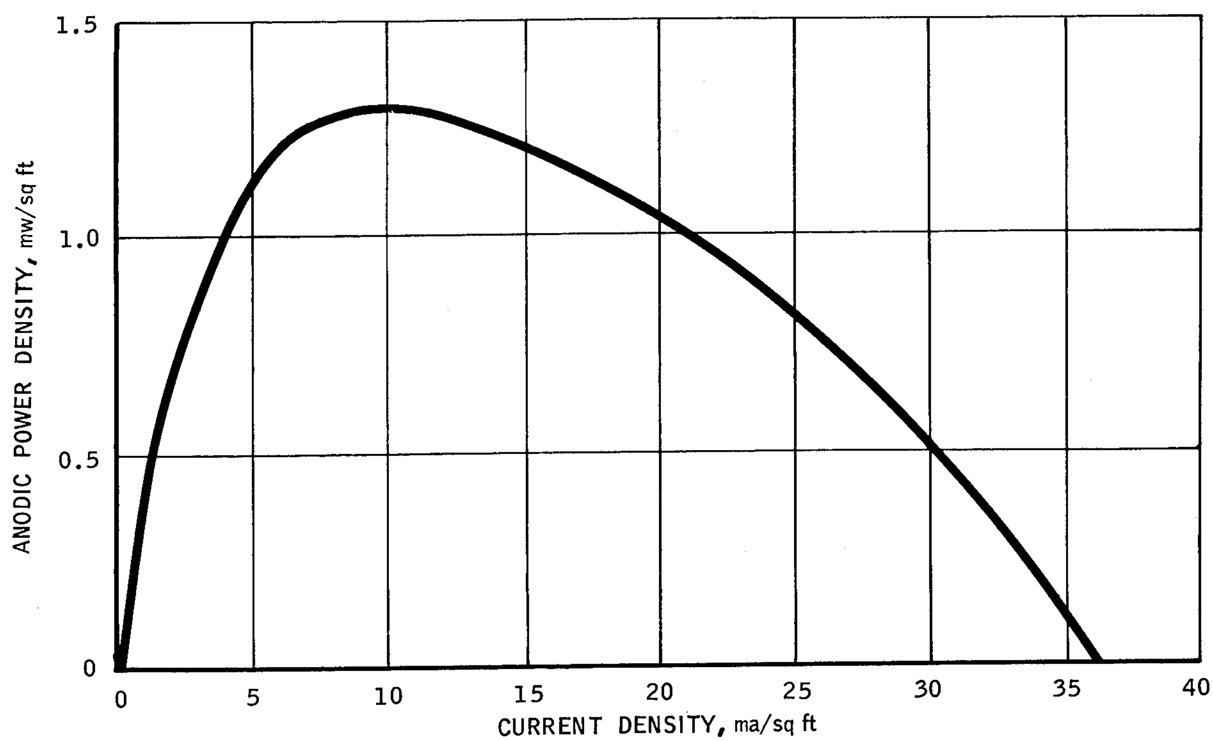

FIGURE VI-6—An anodic-power-density curve. (System described in table I.)

Urine alone has not provided as much electrochemical power as mixtures of urine and feces have, but there appears to be little effect of the ratio of feces to urine above a concentration of 10 grams of feces per 100 milliliters of urine.

Additions of Chemicals or Extraneous Microorganisms

Chemicals and extraneous microorganisms have been added to the human waste in some cases, to test the activities of nonindigenous microorganisms, to increase electrolytic conductivity, or to provide nutrient and buffer pH. Thus far, the additions of extraneous substances have had a negligible effect upon the potential and current of the biochemical fuel cell. Ideally, it may be possible to forego these additions.

Pretreatment (Sewage) Studies

Investigations have been made of the effects of temperature, time vessel material, atmospheric conditions, and pH in pretreating human waste to increase its electrochemical activity. An examination of the effects of these variables, in the order given above, shows that there was no significant effect of temperature over the range from room temperature (75° F) to a standard incubation temperature (95° F). The open-circuit potential increases during the first few hours of an experiment, then decreases slightly, and reaches a plateau. The metals and nonmetals used in these systems have been tested by placing the material in contact with a suitable microorganism and nutrient on an agar plate, to ascertain that they do not poison the microorganisms. Anaerobic conditions have been used thus far, but aerobic studies are being initiated. Maintaining the pH at 6.0 to 7.0 has not been as beneficial as allowing the pH to follow its natural course; it usually rises from an initial pH of 6.0–7.0 to 8.7–8.9 during an experiment.

Selection of Standard Experimental Conditions

Emphasis is being placed at the present on studying the fuel-anolyte. Therefore, in the interest of maintaining standard conditions wherever possible and varying only the fuel-anolyte, the conditions depicted in table I were adopted.

Reproducibility

Standard reproducibility runs are made periodically in both the flow and nonflow apparatus, to verify that the system is the same and invariant with time, and to eliminate questions regarding the effects of possible contamination and of changes in sources of materials or in techniques that may vary over an extended period of time.

The experimental conditions are usually the same as those listed in table I. However, reproducibility studies have been made on fuel-anolytes of varying complexity, from a pure culture of microorganism in nutrient to the final feces-urine mixture containing indigenous microorganisms. The reproducibility attainable with all of these systems has been satisfactory.

Microbiological Research

The developmental aspects of the biochemical fuel cell require that only a limited microbiological research program be conducted. Indigenous organisms must be accepted, since there is no practical means at present of sterilizing human waste in space travel.

The indigenous microorganisms will grow according to their biochemical capabilities and the given nutrient and physical conditions of the biofuel cell. The complex nature of the metabolic reactions can be recognized in view of the different types of organisms that might grow; the range in numbers of any type of organism that may be eliminated in human waste, due to variations in diets; human physiological variance in intestinal digestion of food; and microbiological variations, such as mutation and synergistic and antagonistic reactions between microbes.

The supply of human feces used in the experiments described in this paper was obtained by combining the fecal output of several apparently healthy individuals on a special simulated low-cellulose space diet. The feces were then frozen and stored for convenience and to retard further bacteriological reactions.

Though the system in space might contain

indigenous microorganisms, a limited amount of study is being devoted to determining the effects of selected microorganisms upon the feces-urine mixtures, both sterile and nonsterile, and learning something of the reactions occurring.

Use of Indigenous Microorganisms

Organisms from the indigenous mixture in feces and urine are being isolated. Several gram positive rods (*Bacillus* species by morphology and culture), several gram negative rods, and one gram positive coccus have been isolated thus far. Precise microbiological identification will not be performed unless a microorganism shows significant electrochemical activity in the fuel cell.

Separation of Chemical-Electrochemical Reactions From Biochemical

Chemical-electrochemical reactions were separated from biochemical fuel-cell reactions by isolating the microorganisms from the anode by means of suitable separators (cellulose-acetate membrane or 0.45-micron Millipore filters), so that the microorganisms could not contact and react at the anode. However, any products formed by the metabolic reactions could diffuse through the membrane to the anode.

The data indicated that electrochemically active compounds were formed by metabolic activity, and that these compounds then diffused to the anode and caused an increase in anodic power density over that obtained initially.

Control of Current Withdrawal

A galvanostat-potentiostat, constructed in this laboratory, is used to control continuously the current withdrawn from a biofuel cell at a constant value. The purpose of experiments of this type is to determine the effect of current withdrawal upon the electrochemical properties of a biofuel cell and to determine the total amount of electrochemical energy obtainable from human waste.

A maximum of 47.6 coulombs of current has been withdrawn thus far from a cell containing approximately 80 milliliters of fuel-anolyte mixture.

Bomb-Calorimetric Studies

A bomb calorimeter is being used to determine the heating value of feces, as an estimate of its energy content. The calorimeter was calibrated, and then the heating value of lyophilized feces was obtained (4591–4697 cal/gm).

Maximum Power Levels Attained

Summarizing the experiments conducted thus far, it may be stated that the highest anodic potential obtained has been approximately 0.8 volt (vs. saturated calomel), the best short-circuit current density 105 milliamperes per square foot (under an equilibrium), and the maximum anodic peak-power density 4.0 milliwatts per square foot of electrode area.

Use of Bioelectrochemical Energy for Degrading Human Waste

Studies are being initiated to determine the effects of using bioelectrochemical energy in degrading human waste. The purpose of these studies is to evaluate the degradation reactions of human waste as affected by the bioelectrochemical reactions.

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VII. Transformation of New Knowledge for Economic Growth

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Up to fifty billion dollars and six years hence, we hope to put a man on the moon. During these six years, much new knowledge will be gained in the pursuit of this objective. How can we assure that the billions of dollars spent by the Federal Government in research and development will promote the economic as well as the scientific and military health of the United States? Our national science policy must concern itself with the implications of new knowledge for economic growth, must actively engage in the process of knowledge transformation.

New knowledge in its various forms often can be translated into novel processes, materials, products, and procedures. Some such technological advances increase the quantity of existing goods and services that the economy can produce, while others provide us with goods and services that were not available before and that meet certain needs better than did previously available alternatives. In short, new knowledge that is transformed from specialized space and military uses into commercial uses contributes to economic growth in two ways: it increases the ability of the economy both to produce more of the old and to produce new goods and services. The United States today faces a wide variety of problems. Many of our cities are blighted and congested. First-rate education and health care are available for far too small a proportion of those who could benefit from them. There are pockets of poverty at home, and there is widespread poverty abroad. In order to make a lasting contribution to these problems, it is essential that our economic performance improve and that our economy achieve sustained and rapid growth.

There is a good chance that much new knowledge will ultimately find a variety of useful applications. However, the autonomous transfer or transformation of new knowledge often lags far behind its discovery. For example, Gilfillan estimated that for the 19 most useful inventions introduced between 1888 and 1913, between the time the invention was first conceived and the time it was first brought into important commercial use, an average of 126 years had elapsed! This is too long a period, too chancy a process, and completely inadequate to our present-day growth requirements. Transformation of new knowledge must today be managed transfer.

Knowledge can be considered a kind of capital or resource. It is akin to other economic goods in that it is subject to obsolescence. It may be marketed, processed, stored, distributed, and used in the further production of goods and services. The utilization of new knowledge can proceed along two lines. It can be channeled into uses for which the knowledge was originally intended, as, for example, was the development of the transistor by Bell Laboratories; or it can be channeled into other, unexpected, and, consequently, additional uses. The former, we designate "application" of knowledge; the latter, "transformation" of knowledge. What makes the knowledge-transformation process economically attractive is that it is like finding a use and a market for, say, peanut shells; it is, as it were, a by-product.

While the creation of new knowledge is very costly, its transformation into new uses costs little or nothing.

The creation and transformation of new knowledge contain several contradictory elements, which, if left unexplored, could serve to cancel out their potentially desirable economic effects. First, the results of research are difficult to insulate. Knowledge has no boundaries, unless they are artificially created, and even then they are not easily maintained. New knowledge, whether in the form of new ideas, processes, materials, products, or procedures, spills over from one person to the next, and this fact is of great importance. Knowledge spillover has two negative effects, which lead to great complexity and require an enlightened public policy toward the spillover process. On the one hand, the fear that new knowledge will not long remain restricted in ownership dampens the willingness of private industry to invest in it, even though such investment would be profitable from a national standpoint. On the other hand, spontaneous spillover appears too limited and too slow a process to permit the nation to benefit fully from its large investment in new knowledge. Spontaneous, laissez-faire dissemination of new knowledge therefore leads to underinvestment in private research and development, and while it produces growth, the growth is not as great and as fast as it might be.

It is because of these effects that management and organization of the spillover process become imperative for effective and speedy knowledge transformation. Here, our efforts can be concentrated at the beginning or at the end of the process; that is, we can try to improve either the spill-out or the spill-in of new knowledge. In the case of most inventions, the natural flow of new knowledge is from the inventor to the ultimate user. Improving the process by which the new invention is brought to the attention of potential users involves spill-out management. On the other hand, the user's organized search for new knowledge potentially applicable to his business calls for spill-in management. It is clear that government, quite properly, is concerned mainly with managed spill-out.

Upon careful investigation, however, we can see that expediting the transformation of new knowledge into commercial uses by managing the spill-outs is much more difficult and hazardous than efforts to manage spill-ins. There are very large numbers of new contributions to knowledge being made every month, and each one may have an almost infinitely large number of potential uses and users. The problem of matching bits of new knowledge to its end uses is correspondingly large. On the other hand, the manager of a particular plant has at any one time a relatively small number of problems that can be solved with the aid of new knowledge originating in a more or less small, specified number of fields, and therefore a matching process initiated by the user involves a more manageable number of bits of new knowledge.

In addition to the advantage that the potential user has over the creator in matching bits of new knowledge to end uses, it is also easier for him to translate a potential match into an effective one, because he is often in a position to take definitive action. For example, if the manager of a consumers'-goods division of a company manufacturing electrical equipment assembles a small group of scientists and engineers and assigns them the task of searching the literature and any other sources for methods to improve a given process or to reduce its cost, the manager is in an eminently strong position to initiate action should promising potential matches be put before him. On the other hand, the scientist who creates new knowledge and even identifies commercial applications can at best plead with the industrialist to try out his new method, process, or material. He also might discuss it in scholarly and popular magazines, but his chances of translating a potential match into an effective one are much more slim.

Before we discuss the Government's role in the utilization of new knowledge, I would like to mention some reasons for government involvement in this area. First, new knowledge is being created at a breath-taking rate, and the Government has a dominant role in this creation. However, there is a distinct bias in the emphasis and direction of new knowledge

toward military and defense uses, with a resultant neglect of commercial uses. The Government has the responsibility of correcting some of this distortion.

Another consideration is that Congress appears to be reluctant continually to allocate huge amounts of money for relatively weakly defined objectives of national defense and space exploration. The Department of Defense is using cost-effectiveness analysis and program-budgeting to evaluate some of the defense implications of its budgetary requests. Still, the Defense Department and NASA encounter major difficulties in rigorously defining the implications of their budgets to justify their magnitude. If it can be demonstrated that effective transformation and use of new knowledge will be byproducts of defense and space expenditures and will lead to augmented economic growth, both government and Congress may find their respective tasks eased.

What is the Federal Government doing now to aid the process of knowledge transformation? What should the Government's emphasis be in the future, and what techniques can be used to further its aims?

There are three major federal departments that are making large-scale substantive contributions to new knowledge—the Atomic Energy Commission, the Department of Defense, and the National Aeronautics and Space Administration. The Atomic Energy Commission is engaged in two programs: the Industrial Participation Program and the Technical Information Program. The latter not only concerns itself with the reporting and disseminating of technical information developed through AEC but also operates a comprehensive nuclear-technology information program. The Department of Defense, not required by statute to make its research-and-development findings available to the commercial economy, has done very little in this area so far. Its Armed Service Technical Information Agency, however, provides a central service for the interchange of scientific and technical information of value to the defense research-and-development community. Of the three agencies, NASA has developed the most sophisticated program. It consists of two related efforts. First, NASA-financed programs in research institutes and universities have attempted to provide potential users with information on the new knowledge created by the space effort. Second, the NASA in-house program, which is organized around the Office of Technology Utilization, has attempted to expedite the knowledge-transformation process through technology-utilization officers in NASA centers, and engineers and scientists at Headquarters.

In addition to the work of these three federal agencies, the U.S. Department of Commerce has just initiated a Civilian Industrial Technological Program to supplement and extend the efforts of its Office of Technical Services, which operates as a clearing house for technological, scientific, and engineering information resulting from government-sponsored research.

What are the separate, yet interrelated, roles of government and the industrial community in reaping fuller economic benefits from knowledge transformation? My conclusions are heavily influenced by our new understanding that managing spill-in of new knowledge is much more feasible, potent, and effective than spill-out management. Therefore spill-in management should predominate, and spill-out management should be coordinated with the dominant spill-in approach. It follows that government emphasis should be on research designed to improve methods and administrative procedures for the identification and description of new knowledge, as well as for user-oriented codification. Hand in hand with such research, a number of small pilot projects could be initiated through the establishment of joint government-industry-university codification committees, and through financial support to research institutes specializing in the transformation of knowledge to small and medium-size companies and local government. In addition, about a dozen companies that produce both space products and consumer goods, have dynamic management, and are in an industry likely to benefit from new knowledge might be selected to demonstrate, with the aid of some federal assistance, the feasibility and probability of adapting new methods, materials, processing, and products to commercial uses. This "light-

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house" approach can produce early and rapidly spreading results. Such a step is fully consistent with the profit motive of private industry. The selection of a small number of key companies to serve as experiment and example does have precedent in our economic life. For example, the U.S. Justice Department has for decades used the method of selecting one key company as a target for anti-trust suits in the hope of affecting an entire industry.

However, it is obvious that in addition to improving its own techniques of information identification and codification, the Federal Government will have to take a more active role in encouraging business and industry to invest in the knowledge-transformation process. There are a number of institutional impediments that will have to be removed.

The fact that spillover is a characteristic of newly created knowledge, that, basically, knowledge recognizes no boundaries, works to make participation in the transformation process unattractive to private investors. As a countermeasure, we must evolve a more appropriate patent policy and at the same time provide new, incentive-creating federal tax provisions.

Experience so far has shown that the objective of those companies that do utilize knowledge transformation is limited to the reduction of costs rather than the creation of new products, which involves risk. There is risk in the creation of new products, yet new products are main contributors to economic growth. How can we encourage risk-taking? We can provide more readily available risk capital, at attractive interest rates, for those who are willing to apply new knowledge to the development of new products; and, again, we can consider the use of special tax provisions for these special situations.

Those companies that participate in a major way in the creation of new knowledge—for example, the aerospace companies—are gravely handicapped in diversifying their activities to benefit from knowledge transformation. First, there is some evidence that, rightly or wrongly, many aerospace companies feel that contract officers of the Department of Defense look with disfavor at companies that do not devote all of their energies and loyalty to the manufacture of military hardware. In addition, most aerospace companies are geared to manufacturing products to very fine specifications and high levels of reliability. They are high-cost companies, which have little tradition in the manufacture of inexpensive items for the commercial market. Also, they have little marketing capability and lack commercial market orientation. One result of the lack of market orientation is the evidence that engineers in the aerospace industry, although producing many products for potential patents, generate relatively few patent applications. Some of the unique problems of aerospace companies could be mitigated if defense and space contracts would make provision for some costs for research and development and engineering designed to lead to new commercial uses.

It is obvious that knowledge transformation that is profitable to industry and contributes to the nation's economic growth is a much more demanding and costly undertaking than has been recognized so far, inside and outside of government. A period of excessive optimism about the use of knowledge transformation by industry, lasting through early 1963 and now thoroughly dissipated, appears to have been based on three unwarranted assumptions, bordering on wishful thinking. The first was that NASA and the Department of Defense were providing industry with a great many transferable ideas, processes, materials, and procedures, which could be adapted by many firms with little effort. Then, too, it was thought that the industrial community was anxiously waiting for these possible transfers, and would avail itself of them once firms became aware of the resources that could be had for the asking. Finally, there had been a naive notion that the transfer process was simple, natural, and automatic. A period of more realistic thinking is being ushered in.

The Government must decide whether the financing and administration of knowledge-transformation activities should be carried out by one or several government agencies. The next step that should be taken is government sponsorship of a large-scale effort designed to identify and store new knowledge. It is essential that private industry, universities, and

research institutes be able to retrieve such information easily and apply it effectively on short notice. Such a step will lead to the founding of a great new industry in America, the knowledge-transformation industry. Within a few years it is likely to take its place next to research-and-development and education in the family of knowledge industries. The day may not be far off when private companies will give careful consideration to the question of whether to invest more in research or in building up their knowledge-transformation capability.

Private industry, too, faces a major challenge. It will have to learn how to retrieve stored new knowledge and apply it effectively. There is much evidence that those companies that have a sophisticated R & D capability have automatically created the skills that will make for effective management-knowledge spill-in. In part, this is recognized by business executives. For example, Roy L. Ash, president of Litton Industries, remarked recently, "Companies that are aggressively contributing to new knowledge and staying up to date are freed from 'profit squeezitis'." Those companies that intend to use new knowledge for the production of commercial products requiring high reliability and precision, as, for example, medical instrumentation, are likely to benefit more readily from knowledge transformation than others. Also, state and local governments, which in the past have been very slow in adopting improved techniques, are especially good candidates for managed spill-ins of new knowledge.

California has a particularly significant stake in the transformation of knowledge. In the postwar period, more federal funds have been spent in California on research and development for space and defense than in any other state. California's large investment in education and the resulting high level of education and skills among its labor force offer unique opportunities for future development. A highly skilled and sophisticated labor force can help in the creation of new commercial uses for new knowledge, which in turn will provide new job opportunities at a time when military and space employment appears to have reached a peak in the state. The state government could take an enlightened interest in this process through initiating an integrated knowledge-transformation program on an experimental basis. The high concentration in California of new knowledge-creating industries and skilled manpower makes a state knowledge-transformation program an attractive and rewarding possibility.

As always, the question remains whether the payoff from knowledge transformation will be great enough to justify the necessary costs. Actually, we cannot be sure. But the prospects are good, and the goal of economic growth is so important that we must assume the risk. If we are enterprising, we can visualize the emerging of a new major branch of our exciting knowledge industry. Organized knowledge transformation in years to come is likely to become a joint government-university-private industry effort of major proportions, attracting, it is to be hoped, men of the highest caliber, who will develop a common language between originators and users of new knowledge. The rewards to companies in terms of enhanced profits and to the entire nation in terms of new products for better living, accelerated economic growth, and fuller employment can be large—and they are within our reach.

VIII. Applications of Space Biomedical Research to Problems of Rehabilitation

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The purpose of this report is to point out the congruity that exists between the in-process resolution of certain problems connected with manned space flight and current problems encountered in the everyday practice of modern medicine.

With this congruity established, it is appropriate to expand on the areas within which some physiological research and development currently being accomplished in connection with our national space program can be directly applied to one of the three major divisions of the practice of medicine. These are: (1) preventive medicine, (2) diagnosis and treatment, (3) physical medicine and rehabilitation. It is in this last division that space medical research has produced developments that may attenuate the effects of some terrestrial disease entities that simulate the anticipated effects of chronic weightlessness. Some of the advances in space physical medicine have given new hope to individuals who suffer from loss of extremities, muscular atrophy or dystrophy, or other forms of paralysis. It is possible, therefore, specifically to relate the problems connected with physical medicine and rehabilitation, and to perceive how the space-medicine program of research development can and is benefiting humanity.

Rehabilitation programs and physical-medicine modalities are designed to: (1) separate the patient from the bed and hospital as soon as possible, (2) restore the patient to normal or near-normal activity with minimum time, labor, and materials, and (3) facilitate an early adjustment to work, home, community, and country.

Congruently, space-medicine research programs involve phases of medicine connected with the prevention of chronic weightlessness effects, with proper diagnosis and treatment of problems induced by zero and near-zero gravity, with effects on the body systems, and with proper rehabilitation and physical-medicine programs. The functional aspects of astronaut protection are: (1) to maintain joint motion, muscle integrity, and strength; (2) to maintain coordination, motor skills, and work tolerance; and (3) to prevent unwholesome physiological and psychological reactions.

With the direct relationship of space medicine and terrestrial medicine clearly established, it is apparent that the same functional devices developed in the space-medicine research program can be used in helping physically handicapped individuals to: (1) restore physical function, (2) increase work tolerance, and (3) regain special skills. For example, in the treatment of the hemiplegic case caused by a cerebrovascular accident, the immediate therapeutic objective is re-education leading to active use of the affected extremity. The long-term objective consists of education of the sound extremity to compensate for the loss of function in the affected extremity. The next steps are: (1) to prevent deformities, (2) to treat the deformities if they occur, (3) to retrain the affected extremity to maximum capacity, and (4) to teach the individual to perform activities of daily living using unaffected extremities. The devices developed to assist the astronaut to perform his space duties with a minimum expenditure of energy are directly applicable to

assisting the hemiplegic in the exercise and performance of his normal functions of movement.

Some of the incapacitating functional entities may be due to genetically transmitted factors, trauma, neurological disorders, hematopoietic factors, metabolic factors, disease, or to iatrogenic or unknown etiologies. In any case, muscle weakness and imbalance leading to progressive wasting of the body are the sequellae. A vicious cycle of muscle and body deterioration ensues, as depicted in fig. VIII–1.

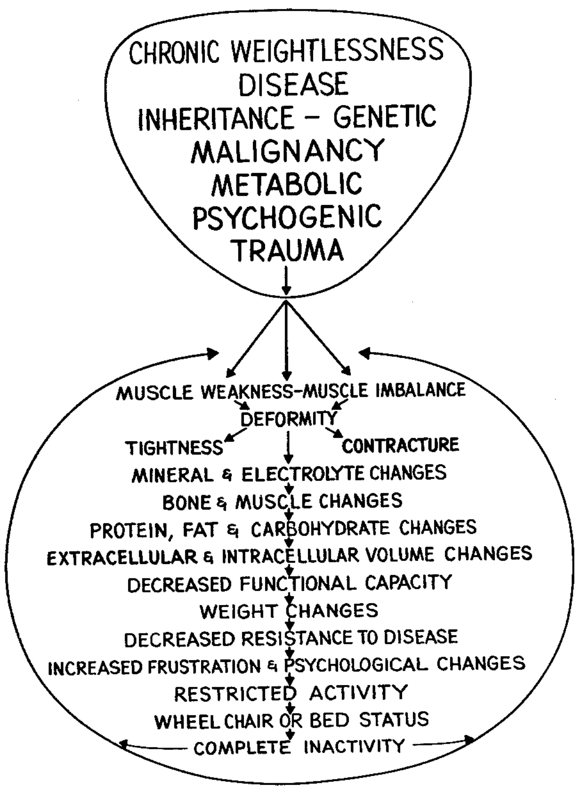

FIGURE VIII–1.—The vicious cycle of neuromuscular deterioration.

It has been learned from experience that many of these conditions are reversible, provided that appropriate remedial measures are started before irreversible tissue changes take place.

In medical literature, one can find well-established disease entities that may simulate the deterioration of muscle tone and mobility due to prolonged periods of weightlessness and restraint. Such conditions are simulated in part by an assortment of disease entities that, if further correlated, would present an over-all picture of the effects on the whole body.

Listed below is a group of terrestrial diseases that may simulate some of the effects of chronic weightlessness and comparable physical conditions on various systems of the human body, especially the neuromuscular and skeletal systems:

(1) Progressive muscular (or nuclear) atrophies.
(2) Progressive muscular dystrophy.
(3) Myasthenia gravis.
(4) Amyotonia congenita.
(5) Myotonia congenita.
(6) Myotonia atrophica.
(7) Polymyositis.
(8) Amyotrophic lateral sclerosis.
(9) Familial myopathies.
(10) Quadriplegia.
(11) Hemiplegia (various etiologies).
(12) Anterior poliomyelitis.
(13) Tabes dorsalis and Charcot's disease.
(14) Adynamic ileus (paralytic).
(15) Myotonia acquisita.
(16) Multiple sclerosis leading to spastic paralysis, disability, and cachexia.
(17) Posterolateral sclerosis (subacute combined system disease).

Some of these conditions are characterized by muscular disfunction in the presence of apparently normal nerve tissue. Others are characterized by a progressive weakness and atrophy of certain groups of muscles associated with neural disorders. Muscular atrophies can result from neural lesions and/or chronic weightlessness. Muscular dystrophies result from primary disease of the muscle itself. Disuse atrophy can occur from a neurological basis of loss of muscle tone, which, in turn, causes disturbances in electrolyte and mineral balance, metabolic defects, loss of protein and nitrogen, and total disruption of homeostatic-metabolic balance.

It has been relatively well established that short periods of weightlessness have little or no effect upon the body. However, prolonged periods of weightlessness may present problems as previously mentioned. As man travels into

space for prolonged periods of time, or establishes and maintains an extraterrestrial base, his remoteness from medical support becomes a critical factor. Research projects are now being performed and proposed to elucidate the medical problems in advance of development of chronic weightlessness effects or prolonged periods of immobility in space suits. For example, research is being conducted at (1) Texas Woman's University, "Fundamental Investigation of Losses of Skeletal Minerals During Prolonged Immobilization, Including a Study of Reducing Mineral Loss"; (2) Frost Engineering, Denver, "Dynamics of Human Restraint"; (3) Mayo Associates, Rochester, Minnesota, "Study of Effects of Sustained Acceleration on Man"; (4) Albert Einstein College, New York, "The Effects of Isolation, Sensory Deprivation, and Sensory Rearrangement on Visual, Auditory, and Somasthetic Sensation, Perception, and Spatial Orientation"; (5) Emory University, "Effects of Zero G and Radiation"; (6) Aerospace Medical Research Laboratory, Wright Patterson AFB, "Caloric, Protein, and Water Requirements of Man Subjected to Simulated Space-Flight Stress."

Motion is a fundamental property of living matter, from the cellular level to the highest form of animal life. In man, motion is based upon transmission of impulses from a receptor, through an afferent neuron and ganglion cell, to the muscle. Motor disturbances from any cause whatsoever can cause weakness and paralysis, which may result in lesions of the voluntary motor pathway, or of the muscles themselves. Impaired motor function may result from involvement of muscle, myoneural junction, peripheral nerve, or the central nervous system. To these causes must be added the involvement due to disuse atrophy and/or the effects of chronic weightlessness due to zero or near-zero gravity conditions and the associated restraint systems over prolonged periods of time.

There are procedures, instrumentation, medication, therapy, etc., being developed for the diagnosis, prevention, and treatment of disease entities such as those simulated by the effects of chronic weightlessness. Additionally, studies of simulated prolonged weightlessness effects are currently being performed on animals and humans. Two such simulated environments are: (1) prolonged bed rest and (2) water suspension. The effects of weightless environment on the total body as well as on individual organ systems are being explored. These experiments are attempting to fill in the uncertainties and to extrapolate known data. There are many terrestrial disease entities being diagnosed that develop and present signs and symptoms that simulate the effects of chronic weightlessness (see fig. VIII–2). These, too, are now being studied. This paper is offered in the hope that it may encourage further investigation of terrestrial diseases that simulate the effects of chronic weightlessness, and define problems in advance of the development of such effects.

The results obtained from space-medicine research will undoubtedly help afflicted individuals to a fuller life, through the prevention of muscle atrophy and mitigation of the effects of dystrophy. The devices that will assist the astronaut in maintaining homeostatic function will be therapeutically applicable to those affected with neuromuscular infirmities. For example, the ranking neuromuscular disorders whose signs and symptoms simulate some of the effects of prolonged weightlessness are (1) cerebral palsy, (2) Parkinson's disease, (3) multiple sclerosis, (4) muscular dystrophy, and other demyelinating diseases. These are either or both neuropathic and myopathic. Others are: myasthenia gravis, amyotrophic lateral sclerosis, familial myopathies, anterior poliomyelitis, tabes dorsalis, posterolateral sclerosis, and subacute combined system disease. All leave the mark of muscular disintegration. Calcium losses during weightlessness are dangerous and undesirable. This is also noted as a factor during immobilization of invalids or convalescents due to prolonged bed rest.

Statistics show that about three in 2,700 persons have muscular dystrophy, and two out of three of these are children. These diseases exhibit abnormal distribution of muscle solids, protein content, fat, and collagen. They are characterized by changes in serum enzymes and cardiac muscle; mineral and electrolyte balance, with negative nitrogen balance; bone demineralization; decreased gastro-intestinal activity;

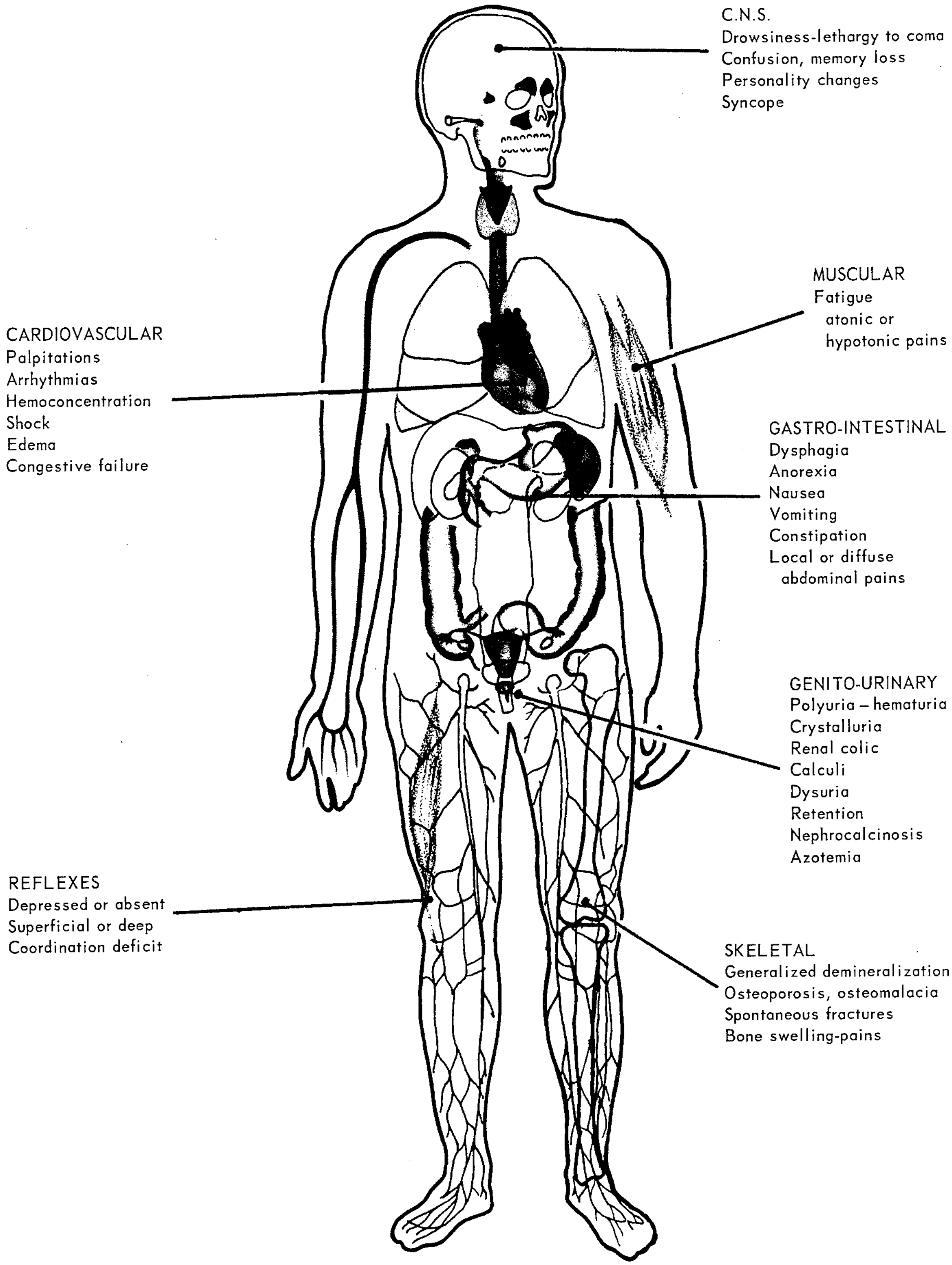

FIGURE VIII–2.—Signs and symptoms of effects of chronic weightlessness with neuromuscular deterioration.

reduction in blood volume; decreased metabolic rate; kidney and urinary changes; and altered superficial and deep reflexes. Similar changes are prognosticated in the effects of prolonged weightlessness of the body. The exercises and devices developed for prevention of some effects of prolonged weightlessness are readily adaptable therapeutics to prevent deformities, treat deformities as they occur, and compensate for impediments that may present an impasse for everyday living.

Medical statistics also indicate that for every 100 persons there are eight with some orthopedic impairment. This rate increases with age. The lower extremities and the hip are the most frequent sites of impairment. There are also over 259,000 cases of amputees on record, excluding cases involving just fingers and toes. These are all potential beneficiaries of the space-research developments. Major improvements in function and appearance of prosthetic devices have made them more acceptable to individuals with amputations. Devices developed or being developed for support of persons with musculoskeletal disease and disability are constantly being improved as mechanisms for more efficient conservation and use of body energy. This is in the fields of biomechanics and biotechnology, which are direct study areas in space medicine.

The continuing study of the effects of chronic weightlessness and neuromuscular disease entities will insure better therapeutic devices and remedial measures and, subsequently, a better understanding of the causes, which may lead to the prevention of, or improved techniques in the treatment of, such diseases. For example, the leg part of a space suit, which in one case has been used to prevent the pooling of blood and fluid in the lower extremities, can act as a pump to facilitate the return of blood and lymphatic fluid to the heart. This will ameliorate stagnation, decubiti, and congestive heart failure. Such a device may also substitute for Buereger leg exercises in TAO and other occlusive vascular diseases of the extremity.

The field of physical medicine will benefit by the development of devices that will rehabilitate individuals at a faster and more efficient rate, with a resulting lower cost to public-welfare agencies. Studies and research programs are now being pursued in the fields of exercise (e.g., isometric exercises), pharmacodynamics, prosthetics, orthotics, occupational therapy, and manipulative and slave devices that are intended to counteract the effects of chronic weightlessness on an astronaut. These same techniques and devices will eventually be applicable to terrestrial entities, to prevent or minimize irreversible muscle or bone damage, etc., as well as to hasten the return of the individual to normal function. One of these devices might be the lunar-gravity simulator at NASA's Langley Research Center, duplicated at Northrop Space Laboratories. Subgravity simulators can be used to rehabilitate patients with neuromuscular disabilities, cardiac ailments, arthritides, and perhaps a host of other conditions that require a graduated activity program.

These advances can be expected to contribute to the economic well-being as well as the purely humanitarian aspect of our nation, by reducing the number of disabled persons being cared for under government programs and making it possible for them to become self-supporting.

This has been a very abbreviated discourse on a relatively small portion of our national space-medicine effort. We believe that throughout the ensuing years the medical profession as a whole will advance substantially through these efforts. This does not mean that the advances will be accomplished only by those directly connected with our national space program. The entire scientific community will, in the future, make contributions to our knowledge that will materially aid in the eventual accomplishment of our basic space objectives. There should be no line drawn between terrestrial and extraterrestrial medicine—rather, the free exchange of our collective knowledge should be our keynote in the never-ending struggle against sickness and disease.

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IX. Glass-Fiber-Reinforced Plastic Structures

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A new, high-strength S(994) glass fiber with HTS finish, when used as filament-wound or fabric reinforcement with an epoxy-resin system, results in a glass-fiber-reinforced plastic (GFRP) material with superior strength characteristics. This glass fiber, when used in a new loom-weaving process that fabricates Raypan truss-core sandwich construction, and when cured with an epoxy-resin system, results in a new lightweight, low-cost sandwich, which promises extensive use in light aircraft structures ~~(ref. 1)~~, powerboat hulls, deep-submersible structures, and other applications. Some of the most noted advancements in the state of the art of GFRP materials and construction that can be attributed to space-age development programs are:

(1) Development of filament-wound pressure vessels.

(2) Advanced orthotropic-material optimum-design techniques.

(3) Raypan loom-woven-fabric sandwich structure.

(4) Development of S(994) glass with HTS finish.

author modified

GFRP construction has the advantages of fewer parts, lower tooling costs, and reduced lead time, resulting in simplicity and tooling flexibility. Additional advantages are aerodynamic or hydrodynamic smoothness, resistance to accidental dent damage, easy repair if damaged, and resistance to mold growth and corrosion. The limitations to this material that have prevented its more extensive use as primary structure have been primarily those of lower stiffness-to-density ratio than metals, and uncertainty that consistent structural weight control and reliability can be achieved in a production operation. The stress-analysis and optimum-design techniques for metals are far more complex in orthotropic (directional-strength) materials, such as GFRP and plywood construction. However, extensive analytical techniques have already been developed for plywood, which can be adapted, and simplifying design charts can be developed.

During World War II, the application of GFRP materials was limited to radomes and antenna housings, which exploited the excellent radio-frequency electromagnetic-transparency properties of this material. Although primary airframe structures were not constructed of GFRP material during this period, another orthotropic material, plywood sandwich, was highly successful as the structural material for 17,000 Mosquito bombers.

GFRP MATERIALS CONSIDERATIONS

Thermosetting Resin Systems

The resin systems used in GFRP materials are thermosetting; i.e., the plastic resin system undergoes a permanent chemical change, called polymerization, or the formation of many giant molecules, when curing occurs. The curing process has stages identified as "A" stage, when the resin is still liquid; "B" stage, after heating, when the resin is a thermoplastic solid; and "C" stage, after further heating, when the resin becomes fully cured and has become an infusible solid. There are now

many resin systems; however, only three will be mentioned here, and the epoxy-resin system, of these three, will be considered in the analytical-techniques section.

Giant molecules, or high polymers, occur in nature as wood, meat, starch, cotton, wool, and silk. Therefore, the challenge to chemists to understand the nature of these products of living things resulted in an understanding of giant molecules. Early experiments sometimes resulted in large organic molecules accidentally. The results were identified as reactions that "resinified" as a gluey, sticky mess. At the turn of the century, L. A. Backland became interested in the gummy liquid formed by a reaction between phenol and formaldehyde. He discovered (and patented in 1905) that by the use of heat and pressure he could turn this liquid into a hard, brittle, transparent "phenolic" resin, which was an excellent insulator. Backland learned that the addition of random fiber filler materials reduced the extreme brittleness and had pronounced reinforcing effects. He also used liquid phenolic resins to impregnate paper and fabrics, thus being the first to develop reinforced plastics, at a time when the new, expanding electrical industry had immediate applications. As a product of the curing cycle, phenolic-resin systems produce water, which, in becoming steam, could develop bubbles, voids, and porosity. Hence, a high pressure (200 to 500 psi) is required in the curing cycle of phenolics to prevent the formation of steam. This high-pressure problem prevented the early use of phenolics when woven glass-fiber fabrics were developed, because the glass would be crushed. In the late 1950's, several low-pressure phenolics (15 psi) were developed, and these resin systems had a strength-retention advantage in applications where temperatures to 500° F were experienced.

During World War II (1942), an advancement was made in the development of polyester thermosetting-resin systems. The distinct advantage over phenolics is that water or volatiles are not a product of the chemical curing process, and thus this resin system has been the most extensively used low-pressure, lowest-cost resin system. Epoxy-resin systems were first produced after World War II, in 1946, and saw extensive use in the 1950's, with a phenomenal increase in use ever since. This resin system also had a low-pressure curing cycle, which results in outstanding characteristics. It produces an excellent adhesive with the highest strength and stiffness, with associated low cost resin system for glass-fiber-reinforced plastic laminates.

Glass Fibers

As early as 1832, and up until the mid-1930's, continuous filaments of glass were formed by heating glass rods and rapidly drawing away the filaments by winding them on a drum. In 1893, a woman's dress was woven from this type of glass material and displayed at the Columbian Exhibition, in Chicago. In the 1930's, both Owens-Illinois Glass Co. and Corning Glass Works carried out considerable experimentation with ways and means of producing glass fibers economically on a commercial scale. These efforts led to the formation of the Owens-Corning Fiberglas Corp., just prior to World War II (in 1938). The main objective and market for this corporation was to produce glass fibers in various random forms for air filtration and for insulation purposes. The corporation had in development an improvement over the heated-glass-rod methods. It was a process now generally used. It was developed for producing glass fibers in continuous strands, and in small enough fiber diameter to be used in the commercial applications of glass textiles. This process of continuous filament production uses glass marbles, heated electrically to bring about melting of the glass. The base of each bushing has 204 drilled holes, through which the molten glass flows under gravity. These 204 filament fibers are gathered together as shown in figure IX–1.

Strand Fabrication

The single strand formed from the 204 filaments is stored on a high-speed collet, which also draws the strand and regulates filament diameter by rotating speed. Just prior to the gathering of the filaments, a complex starch oil is applied as sizing, to ensure that the filaments stay separate and to permit weaving the strands

as yarn to form fabrics later. Filaments may vary in diameter from .0002- to .001-inch, according to the controlled speed of the collet. A code for filament size is given in yards/100 of strands/lb. As shown in the yarn construction of figure IX–1, the 225 code refers to $225 \times 100 = 22{,}500$ yd/lb of strand. This is equivalent to .00025-to-.00030-inch diameter. The 450 code refers to 45,000 yd/lb strand and corresponds to a finer filament-diameter range, of .00020-to-.00025-inch.

The early fiber glass-fabrics produced for World War II bomber radomes were fabricated from soda-lime glass (ordinary bottle glass). When X-band radar was introduced in B–24 (Pathfinder) bombers, in 1942, severe wall reflection from the low-pressure-molded polyester GFRP radomes was experienced. One solution to this problem was made by Owens-Corning, which introduced a low-alkali borosilicate glass, developed specifically for electrical ("E") characteristics. This glass is resistant to attack by moisture and operates in laminates in humid conditions. Hence, since that period this has been the basic composition from which filaments were drawn. As recently as 1962, as a result of Air Force-sponsored research, Owens-Corning developed a new high-strength ("S") glass, designated as S(994) glass, HTS finish. The tensile strength of this glass as reinforcement material is 40 percent higher than the "E" glass, and it retains a higher strength at temperature. The sizing process for filaments shown in figure IX–1 has always been applied to improve handling properties. While these reduced fuzzy and broken filaments in the twisting and weaving operations, they were incompatible with the resin systems. A supplementary heat-cleaning operation was necessary to remove these materials, by exposure to 700° F for extended periods. The fabric was then "finished" by applying a coupling agent to improve the resin-to-glass bond. The HTS finish, which was also developed in 1962, is also applicable to "E" glass, but its real usefulness in combination with "S" glass is to provide a treatment for a strong epoxy-resin glass bond and a strand with characteristics needed for twisting and weaving. Thus the operations of heat-cleaning and finishing are eliminated, with substantial improvement in composite-laminate properties. A comparison of filament and strand (204 filaments) strength properties is shown in table I.

This table shows a considerable strength improvement and a significant modulus-of-elasticity improvement of "S" glass over "E" glass, with a slight reduction in density for "S" glass. These improved properties form the basis for considering S(994)–HTS glass an advancement in the state of the art for GFRP laminate construction.

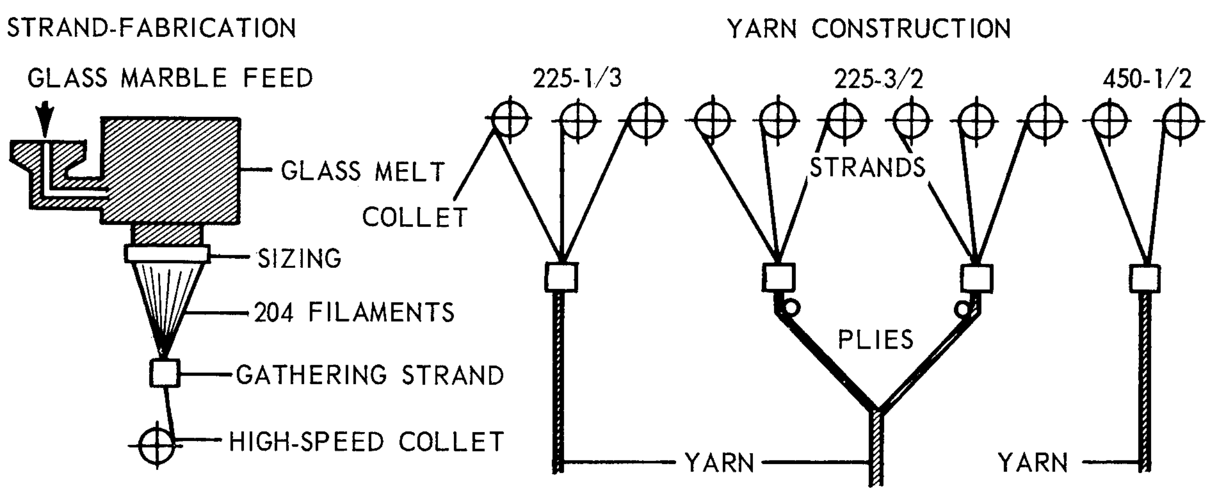

FIGURE IX–1.—Strand fabrication and yarn construction.

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TABLE 1.—*Strand-Strength Properties*

Glass type—sizing strand size	E–801 ECG 140's	E–HTS ECG 140's	S(994)–HTS SCG 150's
Density lb/cu. in.	0.092	0.092	0.090
Modulus $E/10^6$	10.5	10.5	12.4
Stiffness/density (E/D) $\times 10^{-7}$	11.4	11.4	13.8
Single-filament strength psi	500,000	500,000	700,000
Single-strand strength psi	-----	415,000	590,000

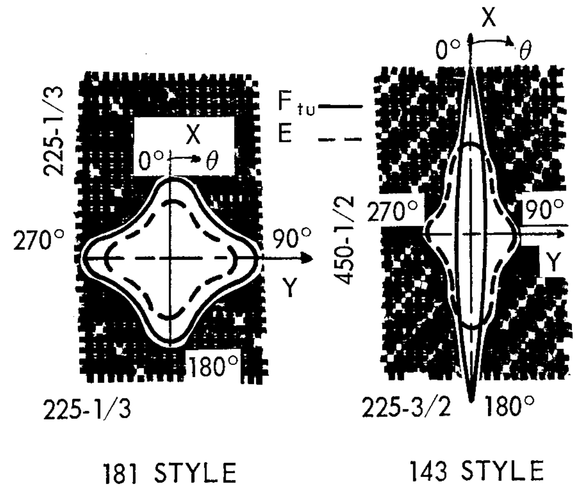


FIGURE IX–2.—Comparison of weaves on 181-style and 143-style fabrics.

Fabric Reinforcements

There are two classifications for fabric-reinforcement woven fabrics and non-woven fabrics. The latter approaches filament-wound construction. Considering woven fabrics, there are approximately 60 styles available. The essential variables are:

(1) Thickness ranging from .0015- to .038-inch.

(2) Weight per sq. yd. from 1 ounce to 2 lb.

(3) Construction (fine yarns—100-ends warp to 80-picks fill and heavy yarns—16-ends warp to 14-picks fill.

(4) Variations in available widths up to 60 inches.

(5) Variation in fabric style.

The fifth variable—fabric style—is governed by required GFRP end use. The three more common styles are:

(a) Plain weave (yarns alternating under and over).

(b) Crowfoot-satin or 4-harness weave (warp yarns interlaced with fill yarns, three over and one under, as in 143 fabric).

(c) 8-harness satin weave (warp yarns interlaced with fill yarns, seven over and one under and staggered, as in 181 fabric).

A basic description of some of the styles in aerospace use follows:

Style weave	Weight (oz/sq yd)	Thickness	Yarns/inch warp fill	Yarn warp	Construction fill
112 Plain	2.12	0.003	40×39	450½	450½
120 4H Satin	3.16	.004	60×58	450½	450½
128 Plain	6.00	.007	42×32	225⅓	225⅓
143 4H Satin	8.78	.009	49×30	225 3/2	450½
181 8H Satin	8.90	.0085	57×54	225⅓	225⅓
181–150 8H Satin	8.90	.0085	57×54	150½	150½

The two fabric weaves that will be considered further are unidirectional 143 style and bi-directional 181 style. Fabric is woven in a warp, or primary, direction and a fill direction, further described as follows:

Longitudinal
  Warp, 0° or X direction,
Transverse
  Fill, 90° or Y direction.

Figure IX–2 shows the weave on the 181- and 143-style fabrics, and an overlay of the strengths and stiffnesses is added. It will be

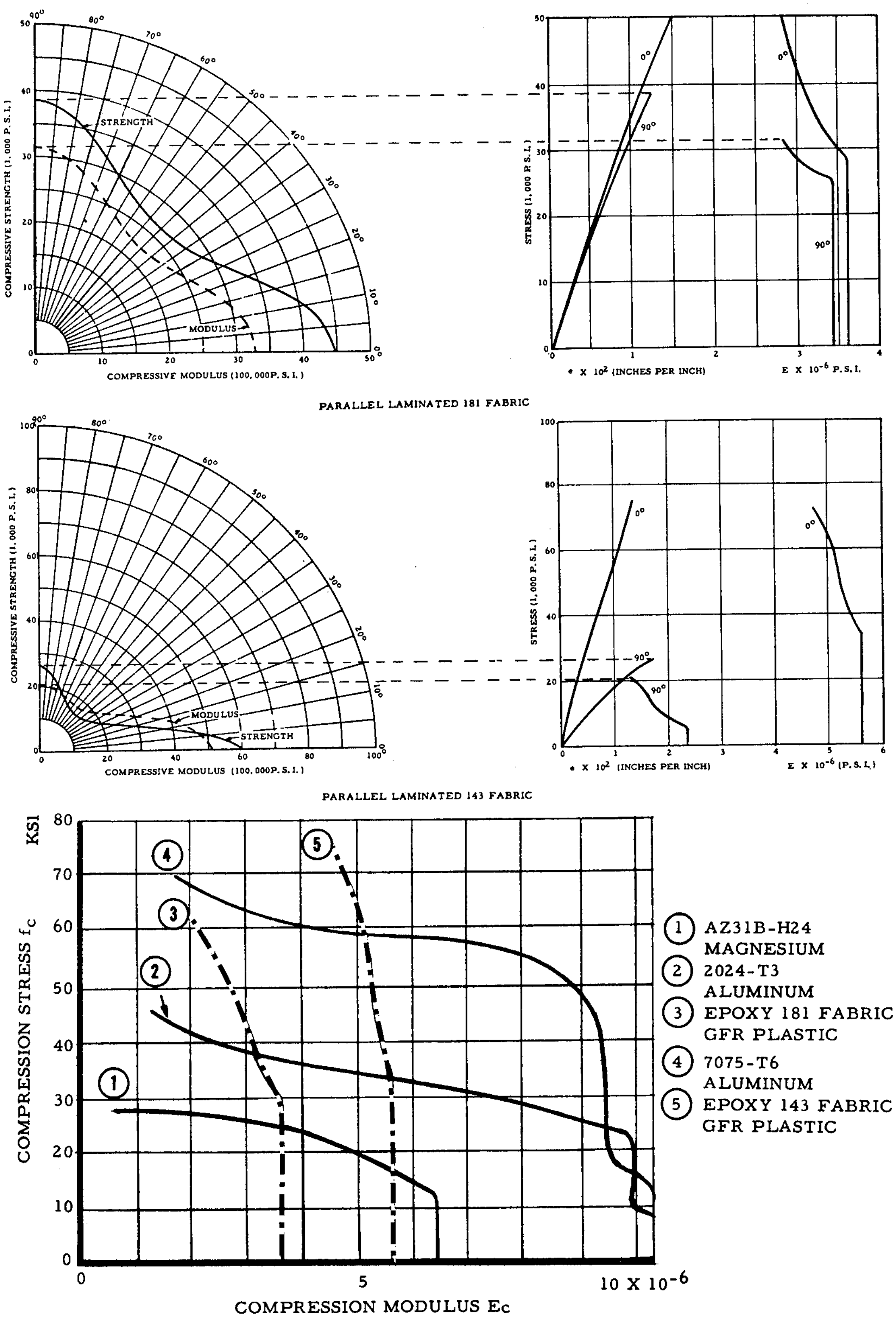


FIGURE IX-3.—Directional-stiffness-strength properties of "E" glass epoxy-GFR plastic with 181 and 143 fabrics, compared with those of metallic materials.

noted that 143 style is considerably stronger and stiffer in the warp (0°) direction and weak in the fill (90°) direction; hence, it is considered unidirectional. The 181 style approaches equal strength in the warp and fill directions and is therefore considered bidirectional. These sketches show the fabric to be weakest in the direction of 45° to the fabric weave. By cross-lamination layup of fabrics to selected directions, a more uniform strength occurs in all directions (isentropic) as against the original orthotropic strength for some reduction in strength and stiffness. Actual directional compressive strength and stiffness values for "E" glass are shown in figure IX–3 for 181 and 143 fabrics (ref. 2). In addition, the corresponding stress-strain curves for 0° and 90° are also shown. The 181-style fabric shows almost equal straight-line-type plots, while the 143 style shows a considerable difference between F_{tu} and E in the 0° and 90° directions. Tangent modulus plots versus stress level are also included beside these stress-strain curves. A further comparison is made of "E" glass 181 and 143 styles GFRP with metallic materials (ref. 3) on a compression-tangent modulus versus stress-level basis. A more significant comparison could be made if density were also included in the parameters. However, interesting facts can be drawn from these curves; i.e., the stiffness of 181- and 143-style fabrics stays almost constant up to compressive failure. The materials remain essentially elastic and have no yield point defined by .002-in./in. offset. At high-stress levels, where efficient structure would be designed, the stiffness of fiber-glass exceeds the commonly used aluminum alloys for a density close to magnesium, which is two-thirds aluminum.

The new S(994) HTS glass demonstrates properties much superior to those of the "E" glass fabrics just described. Table II shows "E" MIL–HDBK–17 wet-strength values and table III provides data on the "S" glass. Considerable increase in strength, particularly for the 143 style, is indicated. A resin content of 33 to 35 percent is the range for woven fabrics.

Three-dimensional and contour-weaving, standard, card-programed weaving equipment has been especially adapted to production of contoured and three-dimensional, sandwich-panel-type, fiber-glass fabrics.

TABLE II.—*MIL–HDBK–17 Data (Wet) Mechanical Properties of "E" Glass and Epoxy-Resin System*

Fabric weave	$\frac{E_x}{10^6}$ (psi)	$\frac{E_y}{10^6}$ (psi)	$\frac{E_xE_y}{10^6}$ (psi)	$1-\mu_x\mu_y$	F_{cu_x} (psi)	F_{cu_y} (psi)	F_{tu_x} (psi)	F_{tu_y} (psi)	F_{su_i} (psi)	F_{su_e} (psi)	$\frac{G}{10^6}$ (psi)
181	3.28	3.14	3.21	0.980	45	38.2	45	42.4	6.79	14.0	0.810
143	5.12	2.08	3.26	0.972	60	26.3	85.0	10.2	3.69	7.86	0.590

TABLE III.—*Owens-Corning Fiberglas Data* Mechanical Properties of S(994) Glass and Epoxy-Resin System*

181 Wet 181 Dry	3.88* 4.01*	3.48 3.37	3.68	0.980	61.1* 62.1*	52.7	88.0* 87.2*	8.21	4.26* 3.95*	18.27*	0.810
143	6.25	2.23	3.735	0.972	81.8	36.3	130.0		2.15	10.26	0.590

The values shown in the table not marked * were ratioed from MIL–HDBK–17 values; i.e.,

$$E_{x_{143(S)}}=E_{x_{181(S)}}\left(\frac{E_{x_{143(E)}}}{E_{x_{181(E)}}}\right)$$

Contour weaving.—Bias-cutting of standard-weave fiber-glass fabrics has been used to prepare the woven reinforcement for laminating into articles with compound curvature. Another method has been developed that represents a total labor saving, although the weaving costs are three to five times higher. This contour-weaving method weaves symmetrical-shaped radomes, cones, and also asymmetrical shapes, such as boxes and boat-hull forms. The circumference consists, then, of one continuous strand. The finished laminate has properties equivalent to those of 181-style fabric.

Three-dimensional fluted-core sandwich.—A three-dimensional weaving process has been developed and controlled by a card program to produce square, triangular, hexagonal, or honeycomb sandwich fabric. The material is identified as Raypan, from Raymond Development Industries, and it represents a significant advancement in the state of the art of sandwich-panel construction. The triangular or double-triangle flute shapes are also called truss-core or double-truss core. The particular advantage of this form of construction is the ability to weave the core integrally to the facing materials. The flute direction is across the loom, and a 144-inch-wide loom has been adapted to production of this type of construction. In the fabrication of sandwich panels, the flute spaces are either left as voids, by inserting removable machined-metal mandrels before applying resin and curing, or else 4 lb./cu. ft. foam mandrels are inserted as accurately cut sectional shapes, and these strips are left in the material. Recent developments to ensure that the entire fabric receives a proper, uniform resin coating have resulted in a "B" stage preimpregnated and marketed product that also provides better weight control for the finished sandwich.

Filament-Wound Reinforcements

The lightest way to achieve the highest directional strength and stiffness is to use unwoven fabrics, or filament-winding, or combinations of both. Woven fabrics lose strength and stiffness, owing to the deflection from a straight line of the woven yarns by the fill material in the case of the warp. The elimination of this inherent weakness by filament-winding has resulted in materials that have displaced the best metals for tensile applications such as the upper stages of the Polaris and Minuteman missiles. In these applications, the structure is a cylindrically shaped internal-pressure vessel with hemispherical ends. The 2:1 stress field can be controlled in filament-winding to provide equal strength in each of the longitudinal and hoop directions. The application of the new high-strength S(994) HTS glass to the Polaris structures has resulted in significant weight reduction, with associated increase in range.

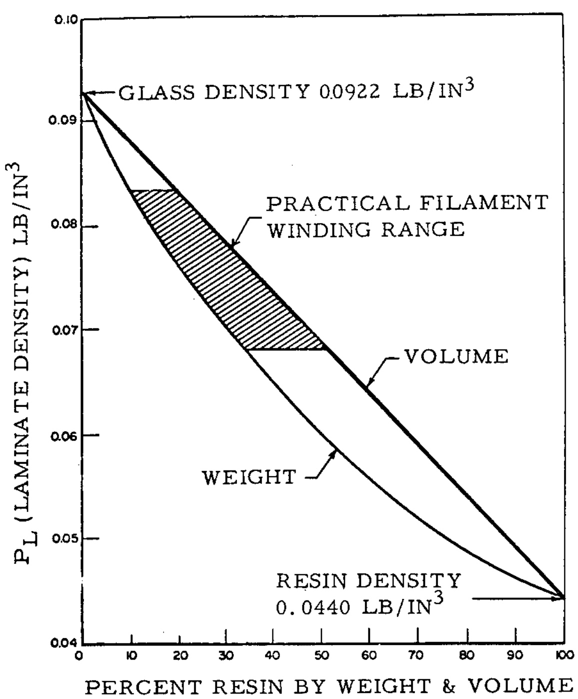


FIGURE IX–4.—Laminate density versus percent resin by weight.

The resin content of glass-fabric laminates is in the range of 33 to 35 percent. The ideal filament-wound structure would seem to be one that practically eliminates the resin. This could be approached if the filaments had a square cross section, but the round sectional shapes allow more room for resin. Figure IX–4 shows the variation of laminate density with

volume and weight for filament-wound construction, with the practical limits shaded. Figure IX–5 indicates by a dotted line the ideal curve for strength, which increases linearly with reduction in resin strength, but resin types I and II do not follow this ideal, and a definite optimum resin content is indicated. It may be noted that the better resin (type I) has a lower resin content.

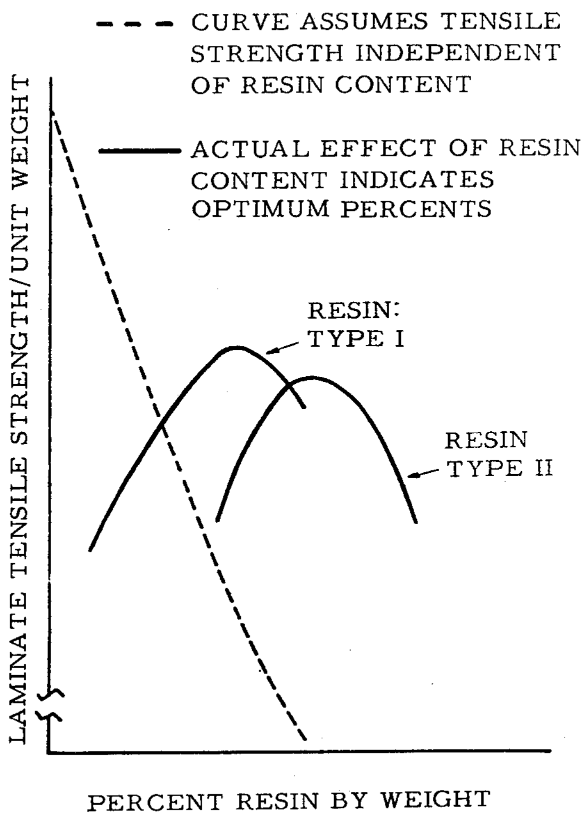


FIGURE IX–5.—Tensile strength/unit weight versus percent resin content by weight.

GFRP DESIGN AND ANALYSIS TECHNIQUES

Analytical techniques specifically applicable to orthotropic materials have been developed for filament-wound internal-pressure vessels and for the buckling-instability analysis of various structural shapes.

Internal Pressure Vessels

Since most classical design formulas for pressure-vessel analysis assume that the material has isentropic characteristics, corrections must be made to these basic formulas to account for orthotropic characteristics such as are evident in filament-wound pressure vessels. An approach originally developed by M. W. Kellogg Co. and later refined by the Young Development Laboratories uses a netting analysis. The netting analysis, which ignores the contribution of the resin strength, is considered valid for simple geometric shapes such as pressure vessels, either cylindrical, with end closures, or spherical; rocket-motor cases; and radomes. The loading conditions in these applications are simple internal loads or combinations of internal pressures and external loads. Actual analysis is too involved for this presentation. However, the basic assumptions for the analysis are therefore:

(1) The fiber-reinforcement "netting" carries all load.

(2) The matrix material serves to equalize loads between fibers by shear-lagging and holds the fibers to the vessel shape.

(3) There is no interaction between layers of fibers wound at different angles.

(4) Thin-shell analysis theories are considered.

(5) The stress distribution across a wall is uniform, and all layers carry the same load.

Buckling Instability

Columns.—The classical Euler-column equation is directly applicable to GFRP construction if the modulus of elasticity used is in the direction of loading. Thus, a load applied to the X direction, or warp direction, of a GFRP column of stable cross section would require the use of a tangent modulus for E_0 or E_x, such as is plotted in figure IX–3 for 181- and 143-style fabrics. Then the buckling-load equation is:

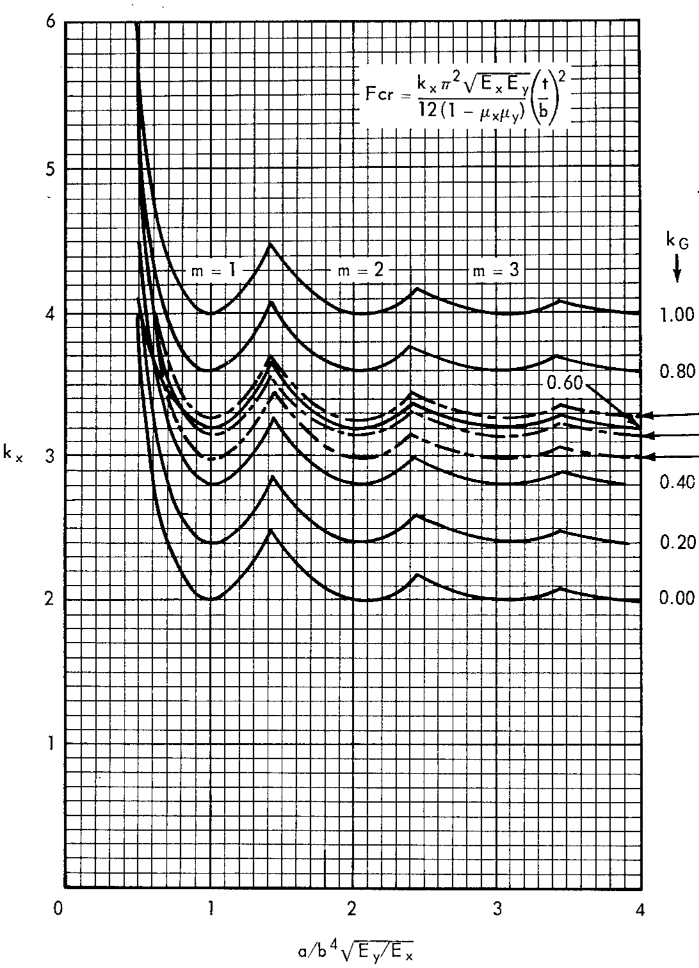
$$P_c = \frac{c\pi^2 E_x I_x}{L^2} \text{ lb}$$

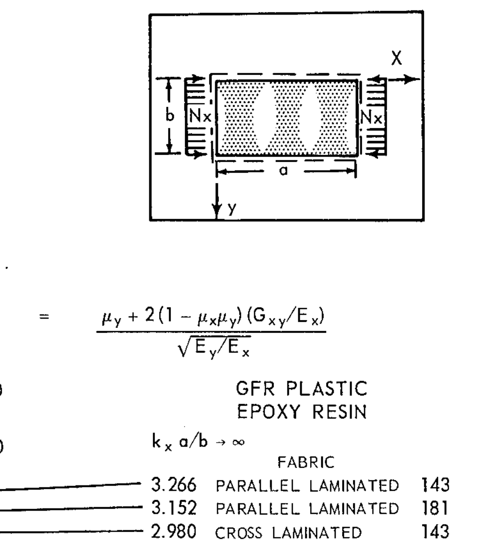
or, to use a buckling-stress equation by dividing by the area and substituting $\rho^2 = \frac{I}{A}$, then,

$$F_c = \frac{c\pi^2 E_x \rho^2}{L^2} \text{ psi}$$

Buckling of plates.—The buckling formulas for isotropic plates were originally presented by Timoshenko (ref. 4) and those for orthotropic plates were originally derived for wood aircraft construction, particularly plywood as used in aircraft construction. The criteria for buckling edgewise-compression-loaded, simply supported panels are contained in reference 2, section 5.3.1.1, and are plotted in figure 5–61 of that reference. The same buckling equation has been plotted as figure IX–6 in this presentation, with the ordinate of reference 2, figure 5–61, changed to k_x.

Figure IX–6 shows that the buckling of an orthotropic plate is a direct function of the square root of the product of $E_x \times E_y$. Also the k_x coefficient is a function of k_G, which is a shear modulus and Poisson's ratio parameter. The comparisons shown in this figure for 181 fabric vs 143 fabric and "E" glass first indicate the k_x value as $\frac{a}{b} \rightarrow \infty$ to be 4.0 where $k_G = 1.0$, as in metals, but is closer to 3.0 for GFRP. A further comparison, including k_x values and modulus values for the 181 and 143 fabrics, indicates a higher buckling strength for 143 style parallel-laminated than for 181 fabric. A derivation of the orthotropic panel-buckling equation that reduces to the plate-buckling





LAMINATED FABRIC	$\sqrt{E_x E_y}$ (psi × 10^{-6})	$\frac{k_x \pi^2}{12(1-\mu_x \mu_y)}$	$\frac{k_x \pi^2 \sqrt{E_x E_y}}{12(1-\mu_x \mu_y)}$ (psi × 10^{-6})
PARALLEL 143	3.26	2.769	9.027
PARALLEL 181	3.21	2.645	8.491
CROSS 143	3.60	2.532	8.756

FIGURE IX–6.—Buckling coefficients for simply supported orthotropic panels loaded in edgewise compression, and comparison of 181 with 143 fabric.

equation for solid sections is given in Appendix A.

Buckling of external-pressure vessels.—The stiffness of the cylindrical pressure hull of a submarine, or of a radome under external pressure, that is partially or completely constructed of filament windings must be known for the longitudinal and hoop directions, in order to determine collapse-buckling strength by use of theoretical formulations. Based on a small deflection theory for buckling of orthotropic cylindrical shells, by Stein and Myers, and assuming a displacement function for a long cylinder of the form:

$$W=W_0 \sin \frac{m\pi x}{L} \sin \frac{n\pi y}{b},$$

the solution for the critical buckling pressure becomes:

$$p_{cr}=\frac{5.51}{R^{3/2}L}\left(\frac{D_y}{1-\mu_x\mu_y}\right)^{3/4}(B_x)^{1/4} \text{ psi},$$

where

B_x = extensional stiffness in the axial direction (x) per unit width (in.-lb)

D_y = flexural stiffness in the circumferential (y) direction per unit length (in.-lb)

L = cylinder length (in.)

R = radius of the cylinder (in.).

Since this is a general equation for the collapse-buckling of an orthotropic shell in the limiting case, it is applicable to a filament-wound shell where D_y and B_x terms reduce to E_y and E_x and wall-thickness terms. Figure IX–7 presents a typical graph for various ratios of E_x/E_y that can be used in selecting optimum ratios of filament-winding in the longitudinal and hoop directions, respectively. Additional aids for converting this required modulus ratio to winding directions (α) and thickness ratios $\left(\frac{t_H}{t}\right)$ are shown in figure IX–8.

Optimum Airframe Structures

Columns and plates.—In 1939, DeBruyne (ref. 5) made a study of the significant material property and characteristics for buckling-efficiency comparisons of metallic materials. These studies were based on the use of a loading-intensity parameter derived from the Euler-column equation. A similar loading-intensity parameter can be derived from the orthotropic plate-buckling equation, which permits efficiency comparison of plates to be made. Figure IX–9 is a graphical weight-efficiency comparison of "E" glass GFR plastics with metallic materials as columns, and also plates, using the loading-intensity parameters. Note that 143 fabric, in the columns comparison, is lighter than the metals over the full range of loading, and that 143 and 181 fabrics are lighter than the metals, compared both as columns and as plates, at the higher loading levels.

Panels and wide columns.—The buckling-strength equation for simply supported orthotropic panels in compression (eq. A–17, Appendix A) indicates panel-buckling strength to be a product of the longitudinal flexural stiffness D_x (eq. A–5), the square root of the transverse-to-longitudinal flexural stiffnesses, $\sqrt{D_y/D_x}$ and $1+k_G$, where k_G (eq. A–19) is a shear term which is a function of Poisson's ratio, μ_y, shear to longitudinal flexural stiffness ratios, $(G\overline{I})_x/D_x$; and flexural stiffness ratios, D_y/D_x. The material properties associated with these stiffness terms are the longitudinal modulus, E_x; the ratio of the transverse-to-longitudinal modulus, E_y/E_x; Poisson's ratio, μ_x; and the shear modulus, G_{xy}. Improvement of the buckling efficiency of GFRP panels is based on increasing the stiffness properties just mentioned without increasing material density significantly. These stiffness properties are a function of the following significant material-fabrication parameters:

(1) laminate layup
(2) fabric weave
(3) resin system
(4) glass filament and finish.

Figure IX–6 showed items 1 and 2 to have a significant effect on the buckling coefficient. Items 3 and 4 have a significant effect on the E_x and E_y modulus terms in the buckling equation. The use of an improved glass such as S(994) HTS therefore improves the buckling-modulus terms and would extend the GFRP "E" glass curves shown in figure IX–9 to higher loading intensities, and shifts them to the right to lower weight.

Another approach to the efficient design of compression-loaded panels is to improve the efficiency of the section properties for the panel, since panel stiffness is a product of the material modulus and its section property. Figure IX–10 presents weight-efficiency comparisons of various stiffened-panel and wide-column cross-section concepts fabricated of S(994) HTS glass in 181 fabric with an epoxy-resin system. These comparisons again make use of loading-intensity index parameters, and the ordinates contain a t term, which represents the cross-sectional area per unit width. The stiffened-panel chart shows the significant improvement in weight reduction in comparing the unstiffened plate with the lightest stiffened panel shown—the truss core, or Raypan-type sandwich. Also shown, for comparison purposes, is the improvement of S(994) glass over the "E" glass. It is interesting to note that positions of panel-concept efficiency are changed when used as wide columns instead of long, simply supported

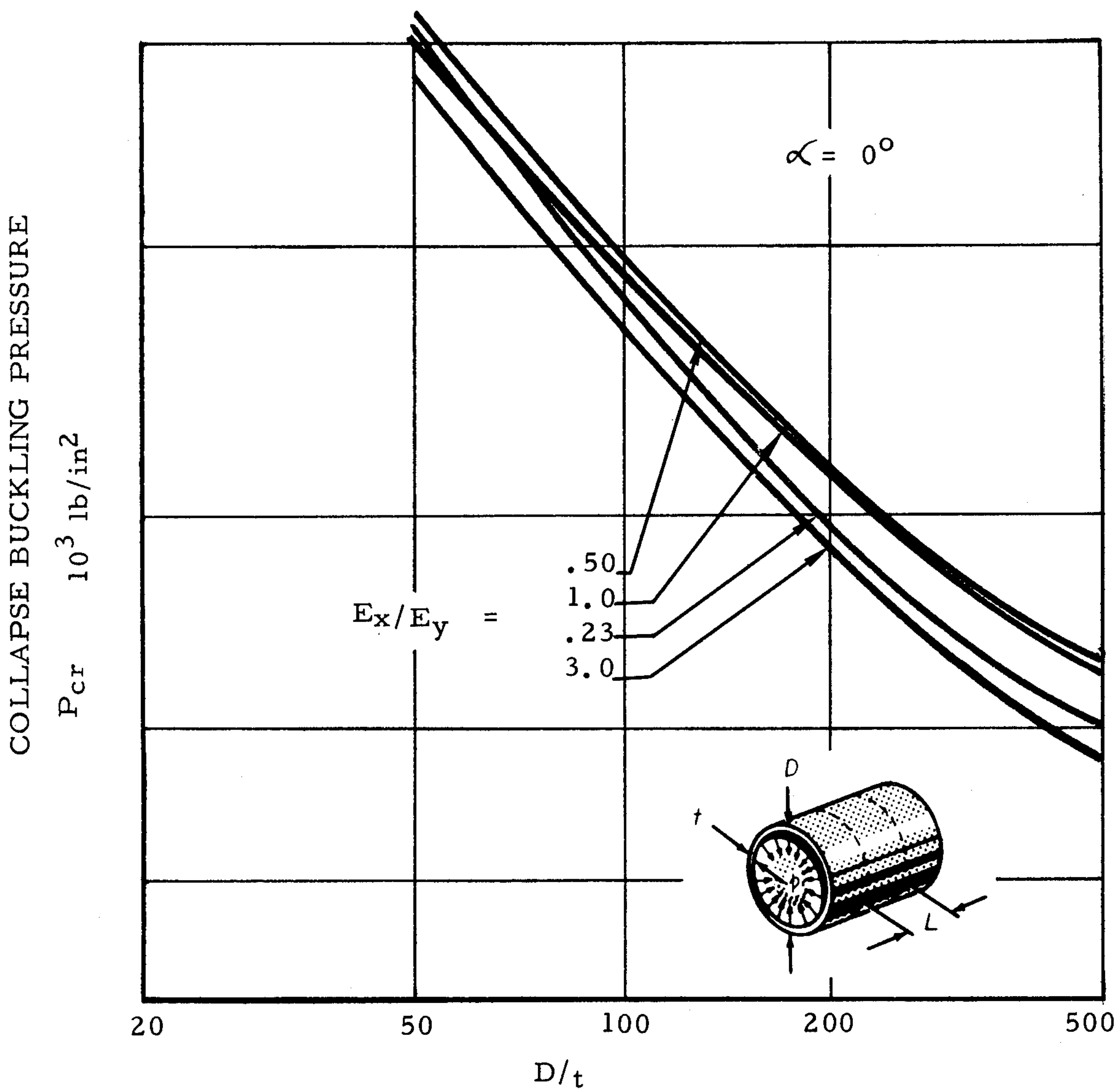


FIGURE IX–7.—Critical buckling stress for 0° and 90° filament windings for various longitudinal and hoop-direction stiffness ratios.

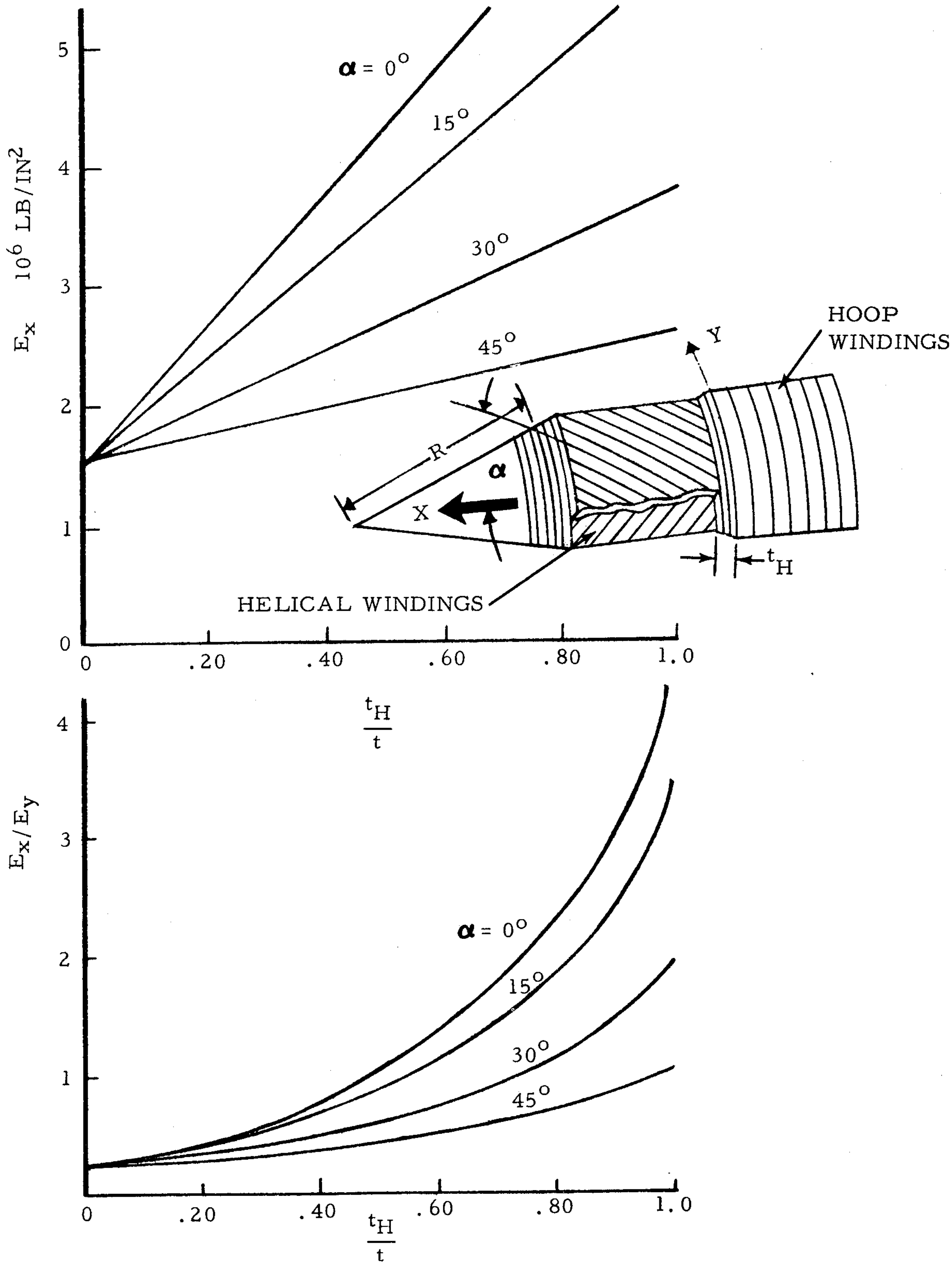


FIGURE IX-8.—Filament-wound composite-wall directional-stiffness control.

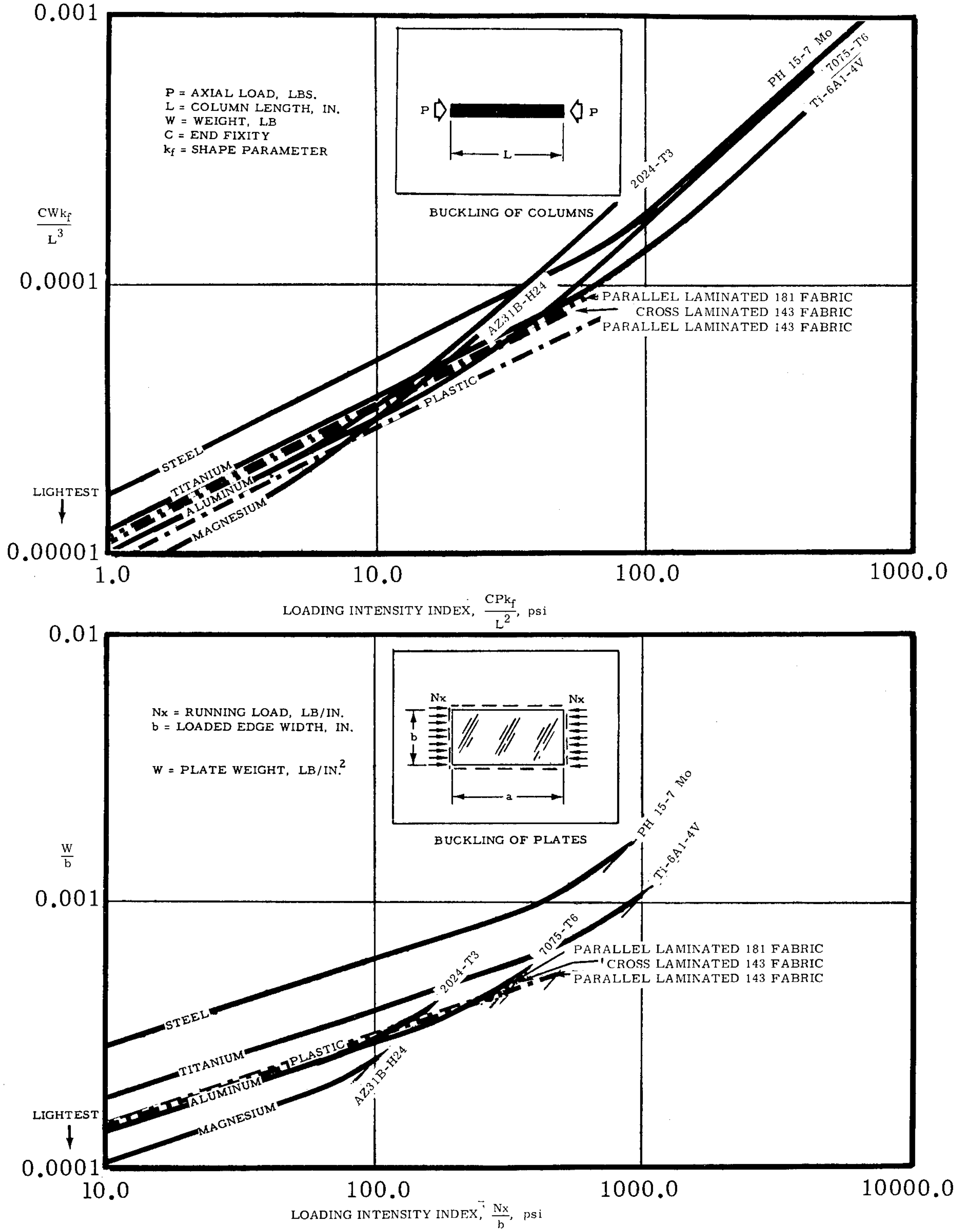


FIGURE IX-9.—Optimum columns and plates weight-efficiency comparisons with metallic materials of "E" glass epoxy-GFR plastic using 181 and 143 fabric.

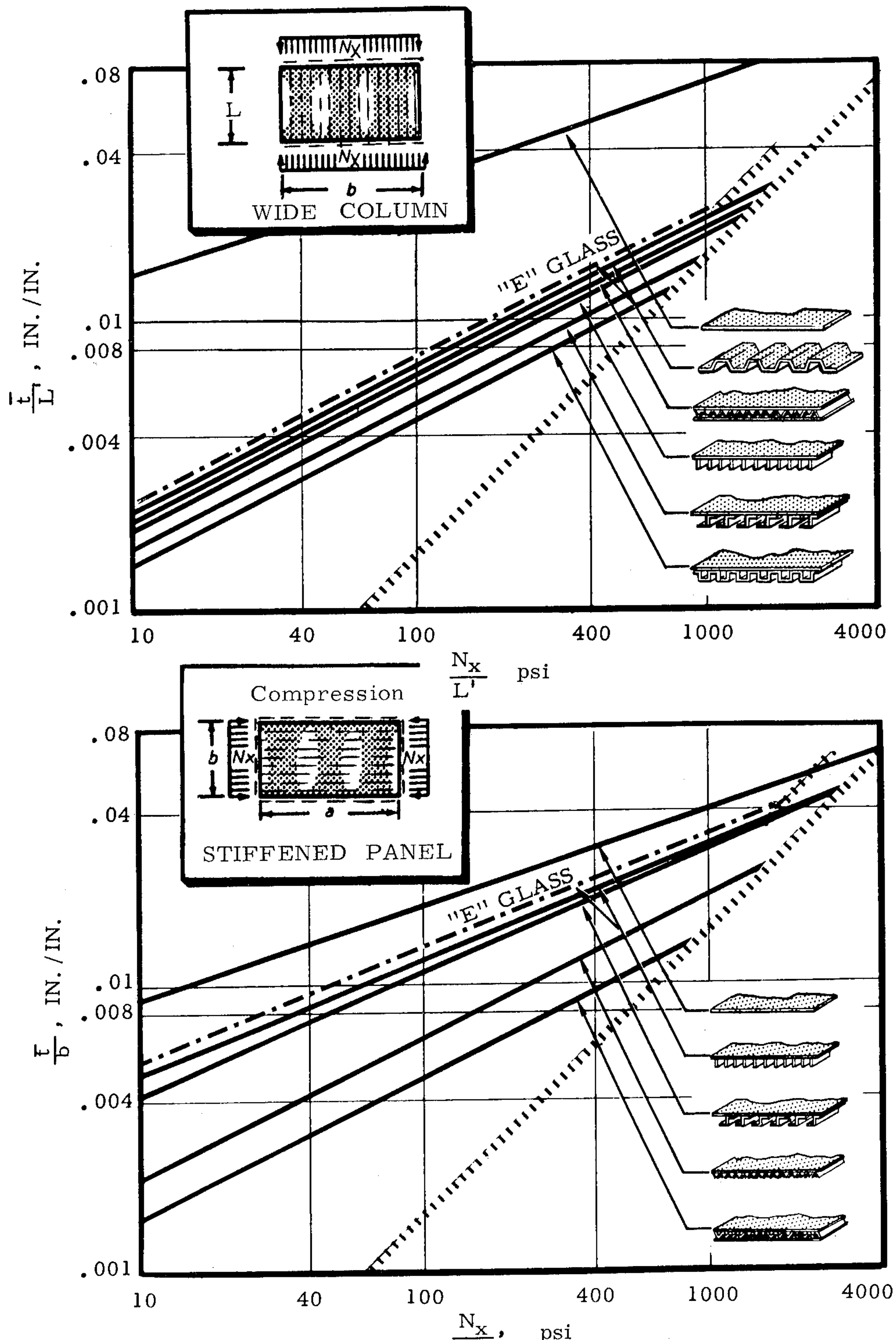


FIGURE IX-10.—Weight-efficiency comparisons of various stiffened-panel and wide-column cross sections of S(994) HTS glass epoxy-GFR plastic using 181 fabric.

panels. This difference can be explained by referring to the panel-buckling equations in the Appendix. Eq. A–14 is:

$$N_{x_{cr}}=\frac{\pi^2}{b^2}\left[D_x\left(\frac{m}{a/b}\right)^2+2D_{xy}+D_y\left(\frac{a/b}{m}\right)^2\right];$$

by multiplying through by $1/b^2$,

$$N_{x_{cr}}=\pi^2\left[D_x\left(\frac{m}{a}\right)^2+\frac{2D_{xy}}{b^2}+D_y\left(\frac{a}{m}\right)^2\frac{1}{b^4}\right],$$

(here a = panel length L).

When the width of a panel becomes very large ($b\rightarrow\infty$), as in wide columns, the last two terms become insignificant. Also, one of these terms contains shear stiffness, D_{xy} (eq. A–7), and the other transverse flexural stiffness, D_y. Thus, panels that do not have large values of D_{xy} or D_y become competitive with panels that do, and, as shown in figure IX–10, prove to be lighter as wide columns.

Methods of improving the structural efficiency of panel cross sections were first studied by Zahorski (ref. 6), and later Shanley (ref. 7), Farrar (ref. 8), and Gerard (ref. 9) extensively employed the optimum-structures design approach, which uses parametric-loading intensity, index-type graphs to compare the weight efficiency of structural concepts for various materials.

The principle of arriving at optimum structural proportions in compression panels, such as the compression side (upper skin) of a wing-box specimen, is based on design for simultaneous general and local instability failure. Panel general-instability failure may be determined by using equation A–17 and A–18 in the Appendix. This equation contains flexural-rigidity terms, particularly the longitudinal flexural rigidity, D_x, which consists of the material modulus, E_x, and the moment of inertia, $\bar{I}_x$, per unit width. If a truss-core sandwich is considered, this section property, $\bar{I}_x$, is obtained for a series of small plate elements representing facing strips and truss web strips, which could buckle locally, according to figure IX–8's orthotropic buckling graph for plates or plate elements. The development of the optimum wide-column buckling-efficiency equations in a manner derived by Crawford (ref. 10) for metallic materials are developed as follows:

applied stress:

$$f=\frac{N_x}{\bar{t}}$$

local buckling:

$$F_{cr}=\frac{k_x\pi^2}{12\,(1-\mu^2)}\,E^{\eta_L}\left(\frac{t_f}{b_f}\right)^2$$

general instability:

$$F_c=\frac{\pi^2\eta_G\rho^2}{L'^2}\,E$$

optimum stress:

$$f=F_{cr}=F_c=F_{opt}$$

combining equations:

$$\begin{aligned}F_{opt}{}^4&=f^2F_{cr}F_c\\&=\left(\frac{N_x}{\bar{t}}\right)^2\frac{k_x\pi^2}{12(1-\mu^2)}\,E\eta_L\left(\frac{t_f}{b_f}\right)^2\pi^2\eta_G\left(\frac{\rho}{L}\right)^2E\end{aligned}$$

which reduces to:

$$F_{opt}=\left(\frac{\pi^4k_x}{12(1-\mu^2)}\right)^{1/4}\left(\frac{\rho t_f}{\bar{t}b_f}\right)^{1/2}(\eta_L\eta_G)^{1/4}\left(\frac{N_xE}{L'}\right)^{1/2}$$

or:

$$F_{opt}=\xi^{1/2}\left(\frac{N_xE\bar{\eta}}{L'}\right)^{1/2}$$

geometry parameters

$$\xi=\left(\frac{\pi^4k_x}{12(1-\mu^2}\right)^{1/2}\left(\frac{\rho^t{}_f}{\bar{t}b_f}\right)$$

substituting:

$$\frac{N_x}{\bar{t}}\frac{L'}{L'}\text{ for }F_{opt}\text{ and transposing}$$

then: $$\boxed{\frac{N_x}{L'}=\xi\left(\frac{\bar{t}}{L}\right)^2E\bar{\eta}}$$

The difference for orthotropic materials will be in the local buckling equation, which now requires E_x, E_y, and G_{xy} properties, as in figure IX–6, and in the general instability equation, which uses E_x instead of E. In the case of

truss-core sandwich panels and wide columns, Anderson (ref. 11) determined an interaction between the local buckling of webs and facings that could give buckling coefficients, k_x, of less than 4.0 even for metals, according to facing to core-web-thickness ratios and truss shapes.

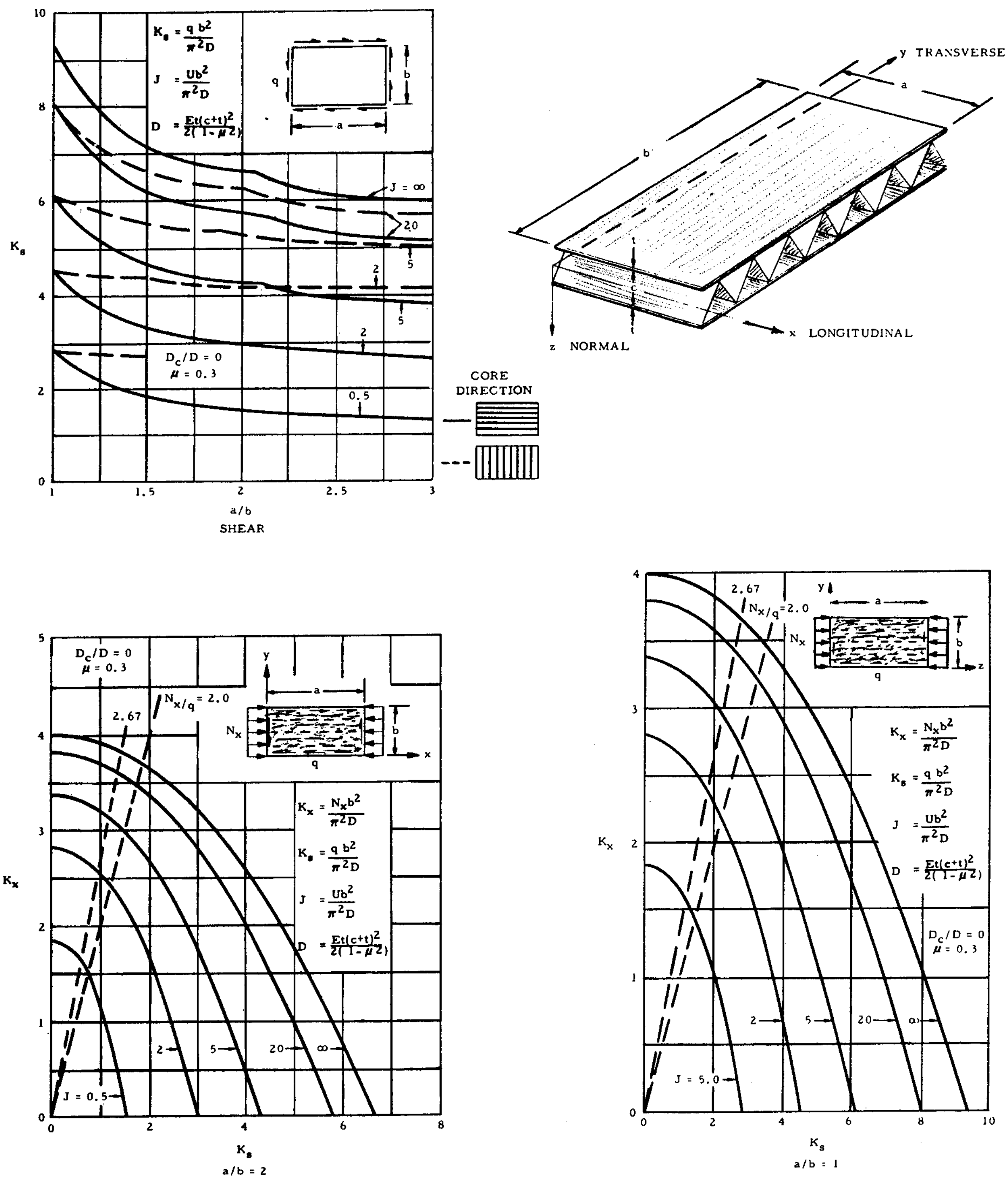


FIGURE IX-11.—Buckling coefficients for corrugated panels under combined shear and longitudinal compression.

Crawford (ref. 10) plotted the grouped geometry parameters vs. basic structural-concept section dimensions to obtain a maximum geometry efficiency, ξ. A similar procedure has been used for panel-buckling graph development, so that figure IX–10 represents a simple presentation of a complex solution, particularly for GFRP orthotropic material.

Figure IX–10 shows the Raypan-type, truss-core sandwich GFRP construction to be the lightest of all fiber-glass panel types. If a fiber-glass sandwich with an aluminum honeycomb core is included, then this construction, though not all GFRP, would be lightest.

The optimum design of panels such as the truss-core corrugated construction requires the consideration of several critical design conditions, such as uniaxial compression, compression and shear, or pure shear. Harris and Auelmann (ref. 12) have developed design curves for corrugated sandwich construction of the type shown in figure IX–11. A particular need that must be satisfied before these curves can be used is to know the transverse shear stiffness, D_{xy}, of the corrugated sandwich. This property is identified in the J parameter as U, and may be determined by testing elements, as in figure IX–12, or through the use of curves prepared by Libore and Hubka (ref. 13).

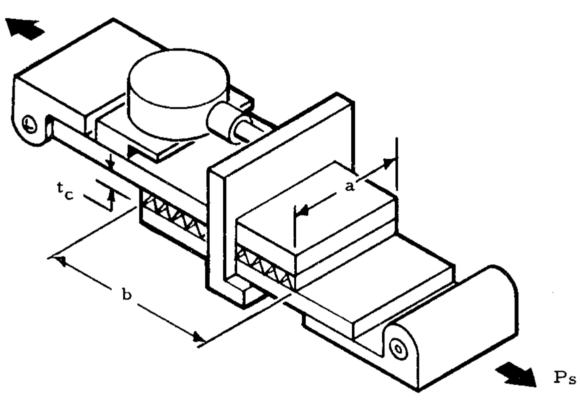


FIGURE IX–12.—Transverse-shear element tests.

To use the combined loading curves of figure IX–11 after the J value has been determined, the slope of a ray line k_x/k_s from the origin must be calculated where:

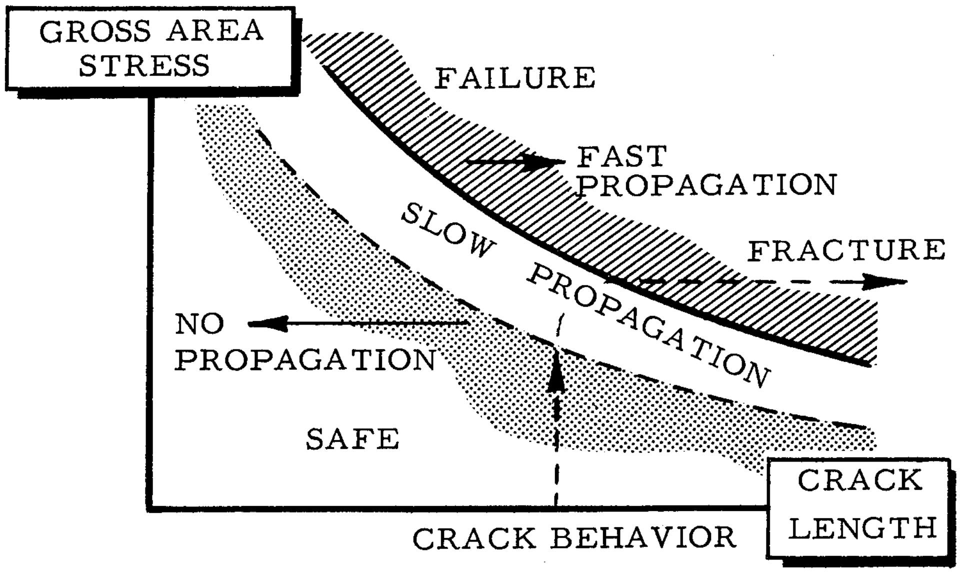
$$k_x/k_s=N_x/q,$$

and N_x and q values are design-compression and shear running loads, respectively. An example ray line is shown in the combined compression and shear curves for $N_x/q=2.67$. The corresponding k_x value may then be read and used in the uniaxial-compression equation with the combined loading N_x. Usually the critical uniaxial N_x value is so much higher than the combined-loading N_x value that the slightly reduced k_x for combined over k_x for $k_s=0$ uniaxial is not critical. The shear curves shown, which would be most useful for Raypan-type spar webs, reveal that the highest k_s value, hence the lightest construction direction for the fluted cores, is parallel to the short edge of the web, or in the transverse direction of the beam web.

Evaluation of Structural Damage

The practical design of minimum-weight optimized structure must also consider the possibility of structural damage. Considering damage to be classified as fatigue damage and service damage, these categories can be further subdivided into fatigue damage due to design, fabrication, or maintenance deficiencies, and service damage due to normal mission hazards, ground handling or erection, and extreme operational conditions.

Fatigue damage may be analyzed for GFRP construction according to established fatigue "safe life" design practices, with the final phase of fatigue life of interest in limiting catastrophic failure to "fail safe" (ref. 14). The damage of a structure may be known due to impact or unknown due to service operations, but the structure should not fail catastrophically. The evaluation of GFRP as a structural panel, box structure, cylindrical shell, or complete vehicle structure for damage limitation requires that the additional considerations of crack-propagation rate, critical crack length, and crack-arresting techniques be analyzed (refs. 15–21). Figure IX–13 shows the type of flat-plate static- and cyclic-loading crack-propagation characteristics that have been used for metals



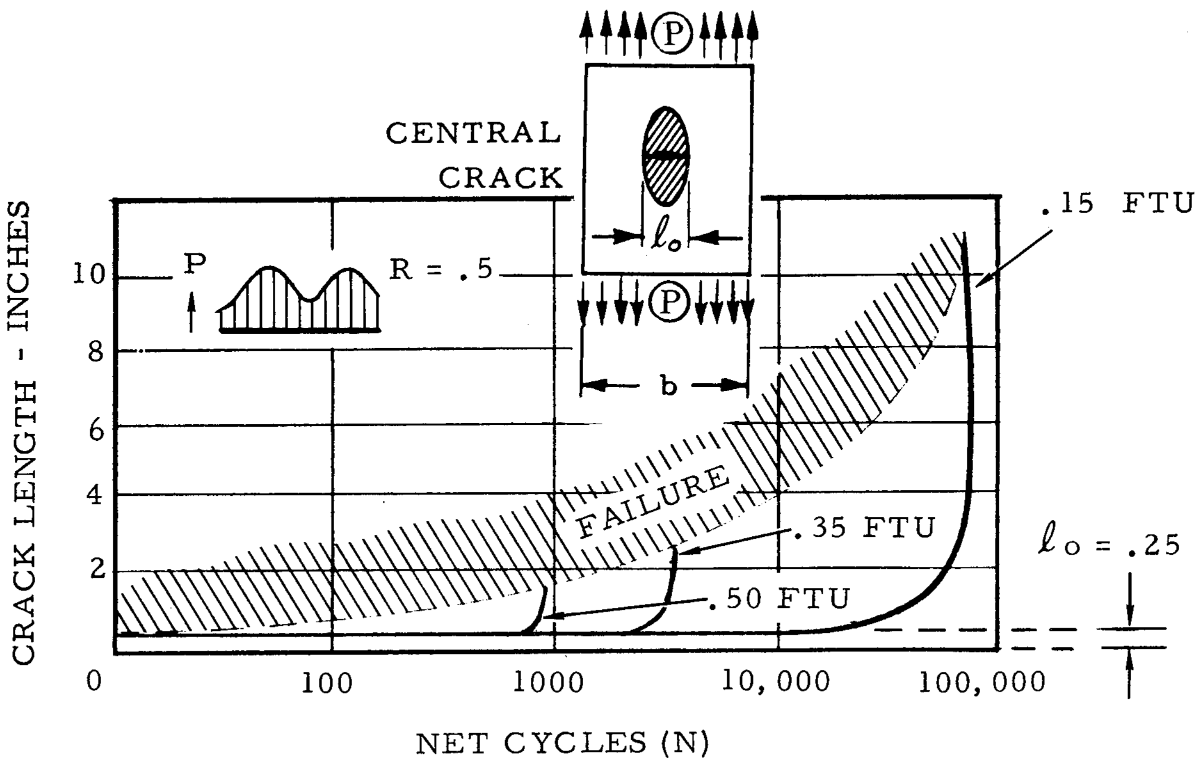


FIGURE IX-13.—Static- and cyclic-loading crack-propagation characteristics.

Critical tear resistance $=\frac{\pi(P^2lCR)}{E(bt)^2}$,

and must be evaluated for GFRP. The tear-resistance equation is also included in this figure. The tear resistance is shown to be a direct function of the square of the operating stress level, and an inverse function of the material Young's modulus. A lower modulus

THE GRIFFITH-IRWIN THEORY $F_{cr} = \frac{1}{C'}\sqrt{\left(\frac{E\frac{dW}{dA}}{\pi x}\right)}$

THE STRESS CONCENTRATION THEORY $K_T = 1 + 2\sqrt{(x/2r)}$

THE "EFFECTIVE WIDTH" CONCEPT

$F_{cr}xt = 2W_e(F_{tu} - F_{cr})$

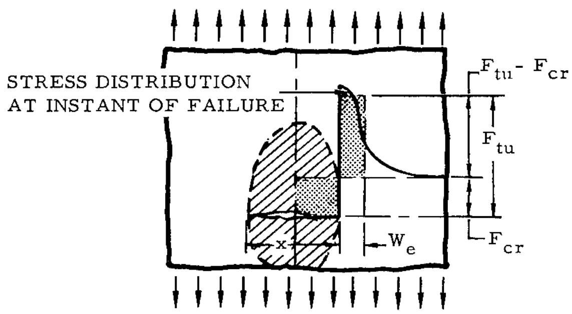
(cut load) = (reserve strength in the skin)

$$F_{cr} = F_{tu}\frac{2W_e}{x+2W_e} = \frac{F_{tu}}{1+(x/2W_e)}$$

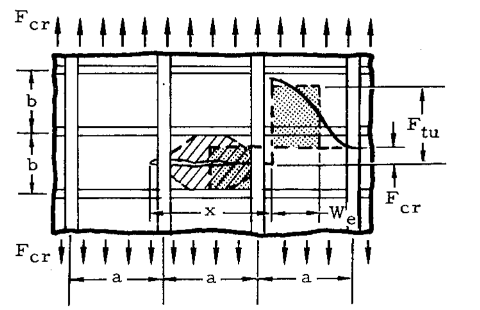
$F_{cr}xt = (F_{tu} - F_{cr})(2W_et + \Sigma A_e)$

(cut load) = (reserve strength of skin and stiffeners)

$$F_{cr} = F_{tu}\frac{2W_e+(\Sigma A_e)/(t)}{x+2W_e+(\Sigma A_e)/(t)} = \frac{F_{tu}}{1+\frac{x}{2W_e+(\Sigma A_e)/(t)}}$$



CRACK PROPAGATION



CRACK ARRESTING

FIGURE IX–14.—Analytical equations for crack-propagation and crack-arresting.

than metals, as is experienced in plastics, would indicate greater tear resistance. Figure IX–14 compares several analytical theories for crack propagation and crack arresting or damage limitation. These theories can be applied to the development of minimum-weight "fail safe" structural-design curves, such as those in figure IX–15. Also shown is the correlation between service operating hours and undetected crack lengths, to establish inspection requirements for structure.

Optimum Pressure-Hull Structures

The equation for the elastic buckling of pressure hulls was developed by Von Mises, in 1914, for tubes of finite length subjected to external radial loading. The theory was extended by him in 1920 to include end pressure and has been widely adopted as design criteria. This theory is associated with the number of peripheral lobes, with more for shorter tubes. Windenburg developed a more simplified expression for elastic buckling by making assumptions with regard to the shape of the lobes, and the resulting Windenburg Trilling buckling equation has been widely used for unstiffened shells. Comprehensive theoretical and experimental work to establish design principles for elastic and inelastic buckling of ring-stiffened shells, including "beam-column" effects, has been conducted at the David Taylor Model Basin. Reports on these results provide very useful graphical and analytical guides for detail design. These references and others serve as a basis for the development of parametric optimum-design charts for the collapse-buckling of shells.

The structural parametric comparison methods that indicate relative weight efficiency of structural cross-section concepts in association with specific materials were developed for stiffened panels by Zahorski and also Farrar, and for cylindrical shells by Gerard and Shanley. The principle of arriving at optimum structural proportions is based on the establishment of geometrical arrangements that result in simultaneous general and local instability failure. Local instability is charac-

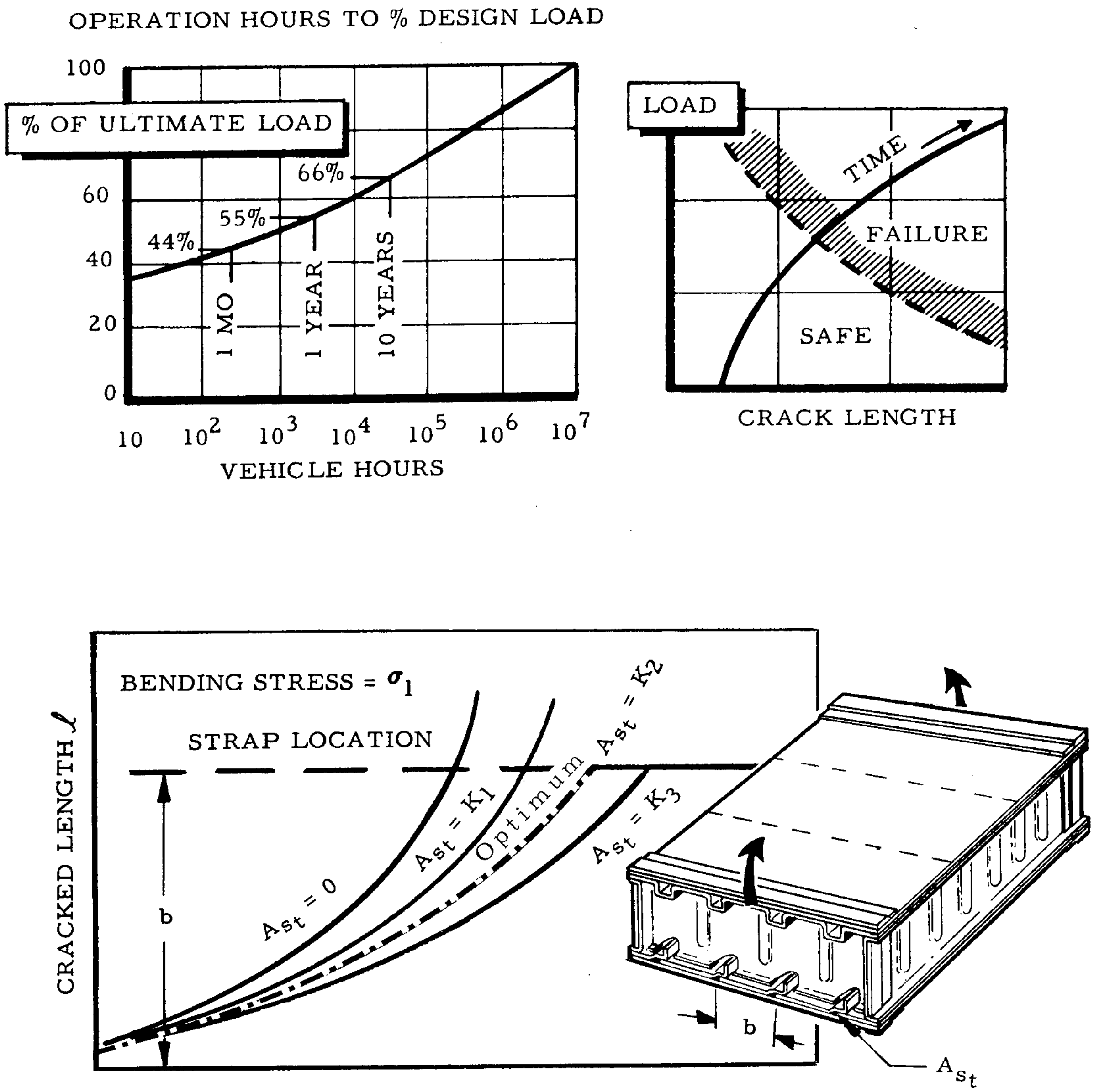


FIGURE IX-15.—Operational considerations for crack growth and detection relationships and determining optimum wing-box strap area for operational-cycles requirements.

terized by local lateral displacement of the shell between frames, or of the frame elements, during buckling, while the lines joining the elements of the configuration remain undisplaced. General instability is characterized by the lateral displacement of both the lines of joining and the elements themselves during buckling. By algebraic manipulation, the equations for general and local instability may be combined and the geometry and material-property terms separated and grouped as parameters. The geometry parameter may be plotted separately to arrive at a maximum geometry efficiency (ξ) in plots for each cross-section concept. This efficiency factor (ξ) may then be adapted into the general material, geometry, and loading-intensity parametric equation of the type developed by Farrar for

wide columns:

loading/material index$=\xi\ x$ (weight index)^n.

In this general equation, as applied to the collapse buckling of shells,

loading/material index=collapse pressure/modulus or$=P_{cr}/E$,

and is plotted as the abscissa. The weight index is plotted as the ordinate and is expressed as: $\rho\bar{t}/R$, where ρ is the shell-material density and $\bar{t}$ is the equivalent shell thickness if all of the material in the cross section were reduced to a uniform solid section of mean radius R. The weight per inch of the shell becomes:

$$W_t=2\pi R\rho\bar{t}.$$

The buoyancy per inch of the shell becomes:

$$B_t=\pi R^2\rho_{\text{water}}.$$

Therefore, the weight-buoyancy relationship becomes:

$$\frac{W_t}{B_t}=\frac{W}{B}=\frac{\text{weight of pressure hull}}{\text{buoyancy of pressure hull}}$$

$$=\frac{2\pi R\rho\bar{t}}{\pi R^2\rho_w}=\frac{2\rho\bar{t}}{\rho_w R}.$$

For graphs that present $\frac{\bar{t}}{R}$ as an ordinate, the weight/buoyancy fraction can be readily obtained by multiplying the $\bar{t}/R$ value by the specific gravity of the material in sea water times 2.

Figure IX–16 presents optimum-design graphs for ring-stiffened cylindrical shells, with a bulkhead spacing of $L_B/R=1.0$ and 4.0. The lower-right-side boundary of these curves represents the optimum-design curve for ring-stiffened cylinders. Reading up from the abscissa, with the P_{cr}/E corresponding to the collapse-pressure depth and the material modulus (E), the first line contacted is the optimum value, and the lines for various L_f/R ratios shown above this line are non-optimum. Thus, the optimum W/B may be readily determined and the results compared with non-optimum geometry. For orthotropic GFR-plastic construction, the E would be modified to an equivalent value, and for metals in the inelastic range, a plasticity correction based on Bijlaard values would be required. An additional capability of this parametric presentation is to enter with an abscissa and a limiting stress level and determine the weight penalty of the non-optimum L_f/R line, which crosses the stress line. Stress lines may be plotted by dividing the abscissa by the ordinate and multiplying the results by E thus,

$$F=\frac{P_{cr}}{E}\times\frac{R}{\bar{t}}\times E.$$

The graphs shown in figure IX–16 are presented for ring-stiffened shells and may be used as a basis for comparison with other concepts. Figure IX–17 presents an optimum-design chart for a truss-core, longitudinally-stiffened sandwich shell plotted for various frame-spacing ratios. As in the previous case, the abscissa may be entered for the collapse pressure and material modulus and the ordinate value $\bar{t}/R$ read and used to determine weight/buoyancy ratio. Detail dimensional layout of an optimum GFRP cross section for figure IX–17 will require the development of specific parametric geometry plots, such as figure IX–18, for each concept.

GFRP STRUCTURAL APPLICATIONS

Marine Vehicles

Deep-submergence vehicles.—The shell structure of submarine vehicles must develop high strength and simultaneously be sufficiently light and practical to fabricate in order to perform effectively with a crew and equipment. Glass-fiber-reinforced plastics, by virtue of their high directional strength, may be utilized to provide high strength/density and stiffness/density ratios in preferred directions.

These lightweight potential advantages of GFR-plastic material are dramatically illustrated in the graph shown in figure IX–19. This graph illustrates lightweight advantages for available and potential GFR-plastic material, particularly at deep depths.

In figure IX–19, a graph is also shown that

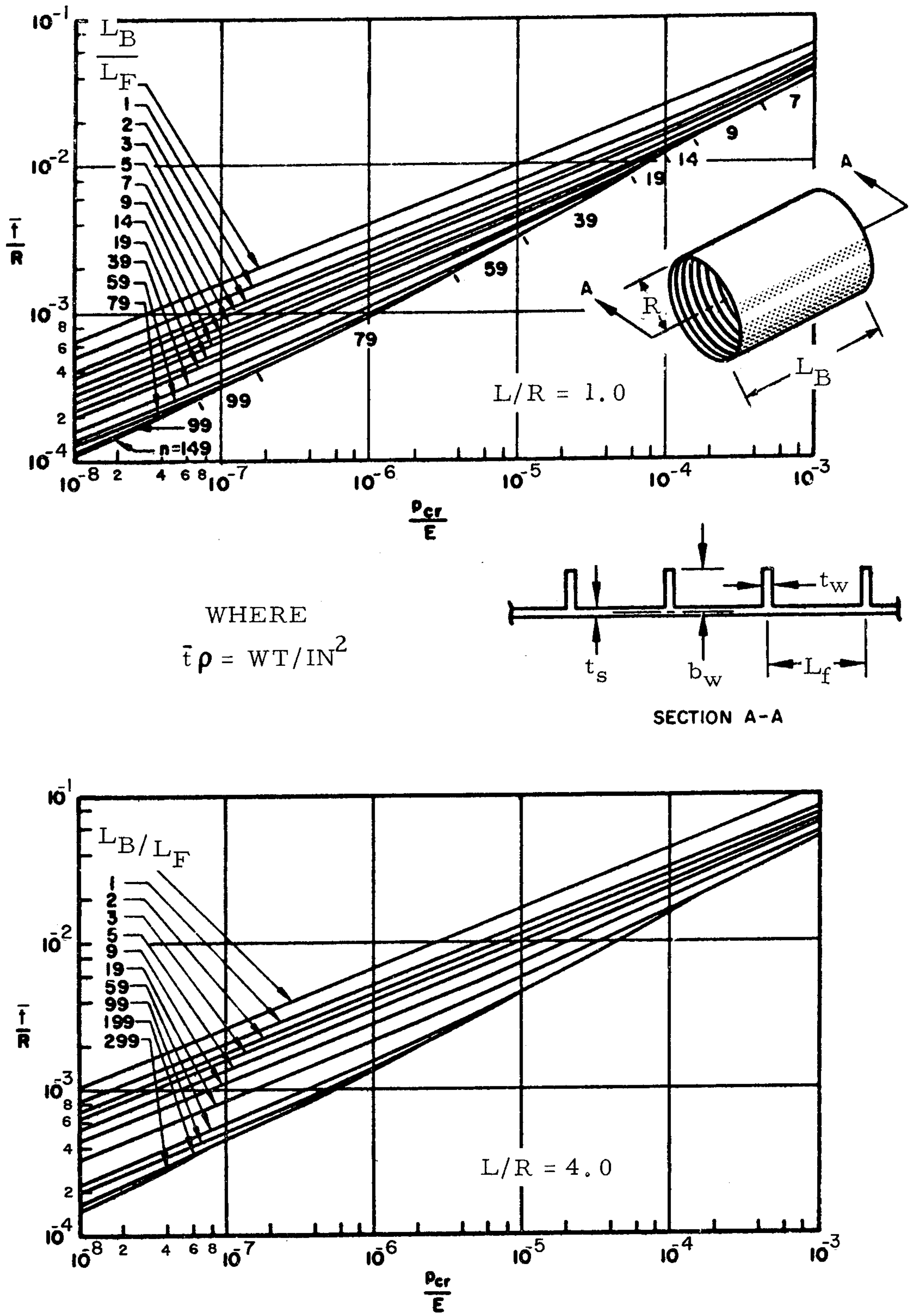


FIGURE IX-16.—Optimum-design chart (when L_B/L_F is specified) for ring-stiffened cylinders under hydrostatic collapse pressure.

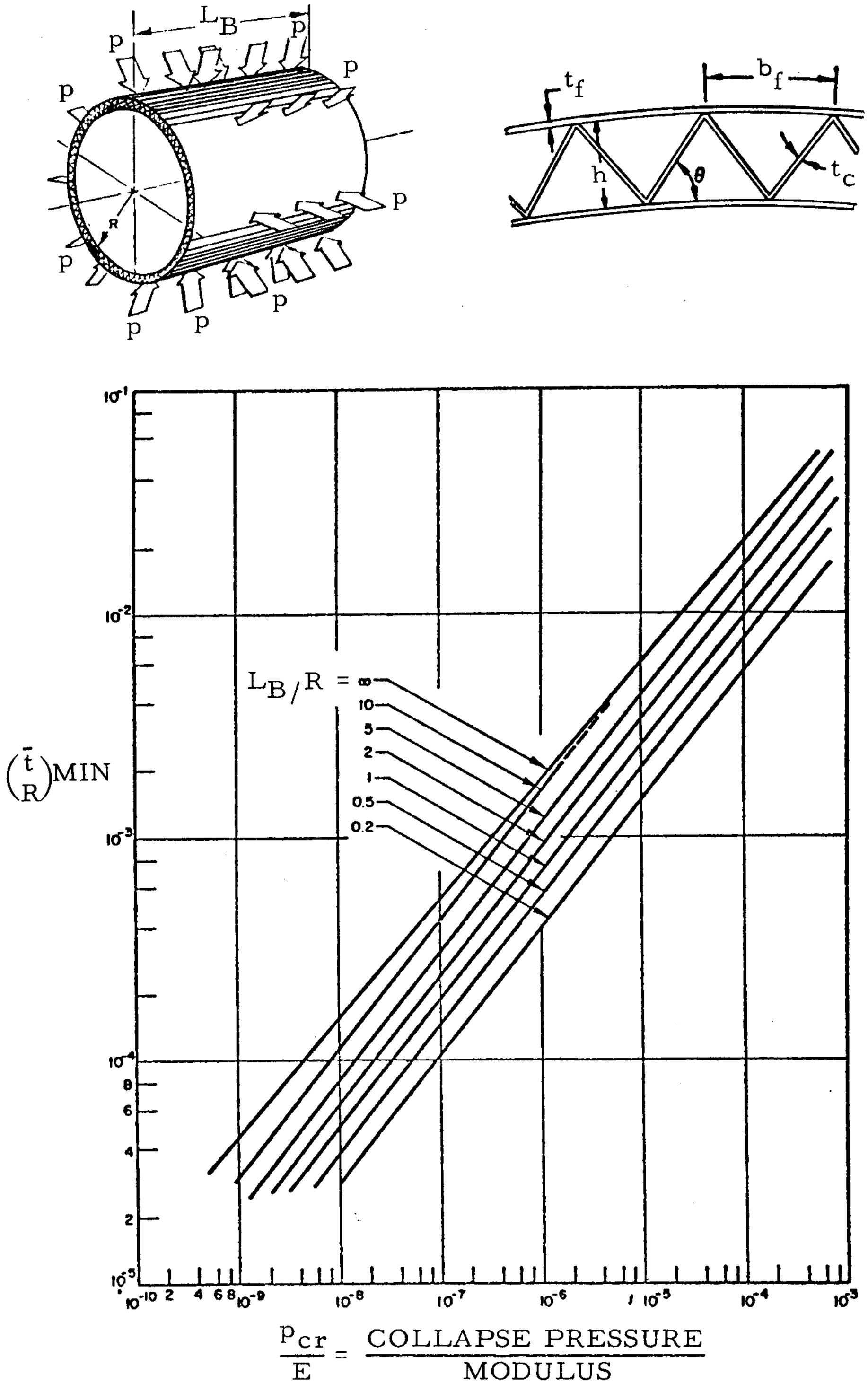


FIGURE IX–17.—Optimum-design chart with various bulkhead spacings for truss-core sandwich cylinders under hydrostatic collapse pressure.

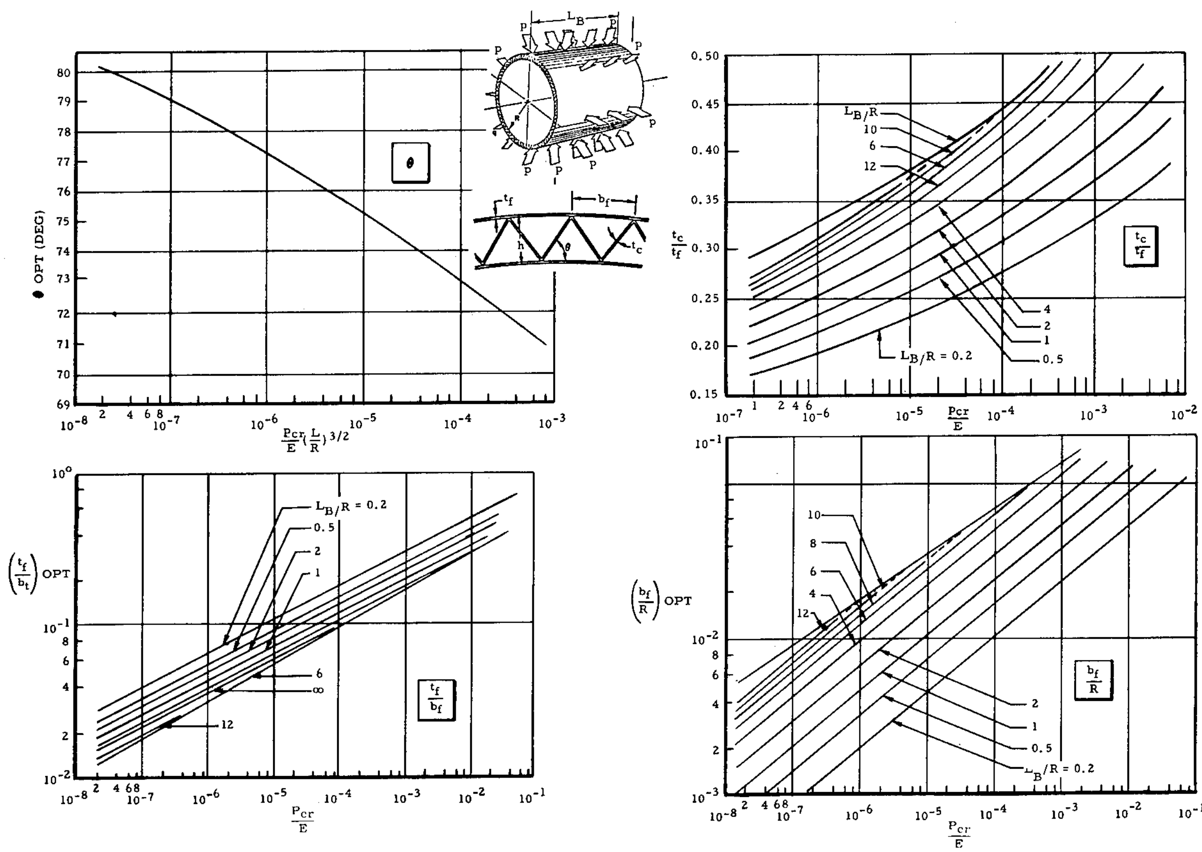


FIGURE IX–18.—Optimum-geometry values of truss angle θ,$t_c/t_f/b_f$, and b_f/R for truss-core sandwich cylinders under hydrostatic collapse pressure.

relates depth of operating submarines and those in the design phase to payload and structure weight. The nuclear submarine is identified with operating depths less than 2,000 feet and hull-structure weights in the region of 22-percent submerged displacement. The Aluminaut, as has been previously stated, is indicated as 60-percent structure, and the Trieste bathyscaph is shown as more than 80-percent structure. Thus, the problem of structural weight in deep-submergence vehicles is of major importance, and representative deep-submergence vehicles will be discussed to establish construction and materials-application trends in association with geometry requirements.

Fleet ballistic-missile atomic submarines.—The fleet ballistic-missile submarine, as shown in figure IX–19, is the product of combining the results of nuclear-propulsion systems of the Nautilus with the hydrodynamically-ideal hull shape, based on NACA airfoil sections, of the Albacore. This combination was exploited in producing a ring-stiffened cylindrical pressure hull constructed of HY–80 steel. The structural characteristics of the pressure hull designed for operating depths below 2,000 feet are long, cylindrical shapes of 30-ft. diameter, with conical transition sections to the forward and aft compartments, which are capped with hemispherical pressure domes. The ring frames are constructed as "T" extrusions of approximately 3-inch flange thickness. These rings are welded to the 2–3-inch-thick hull at two-foot intervals to provide stiffening between bulkheads. Design considerations include a hatch of 23-inch clearance diameter, hull penetrations of various types, and discontinuity joints.

A problem of pressure hulls of this large diameter at these moderate depths is caused

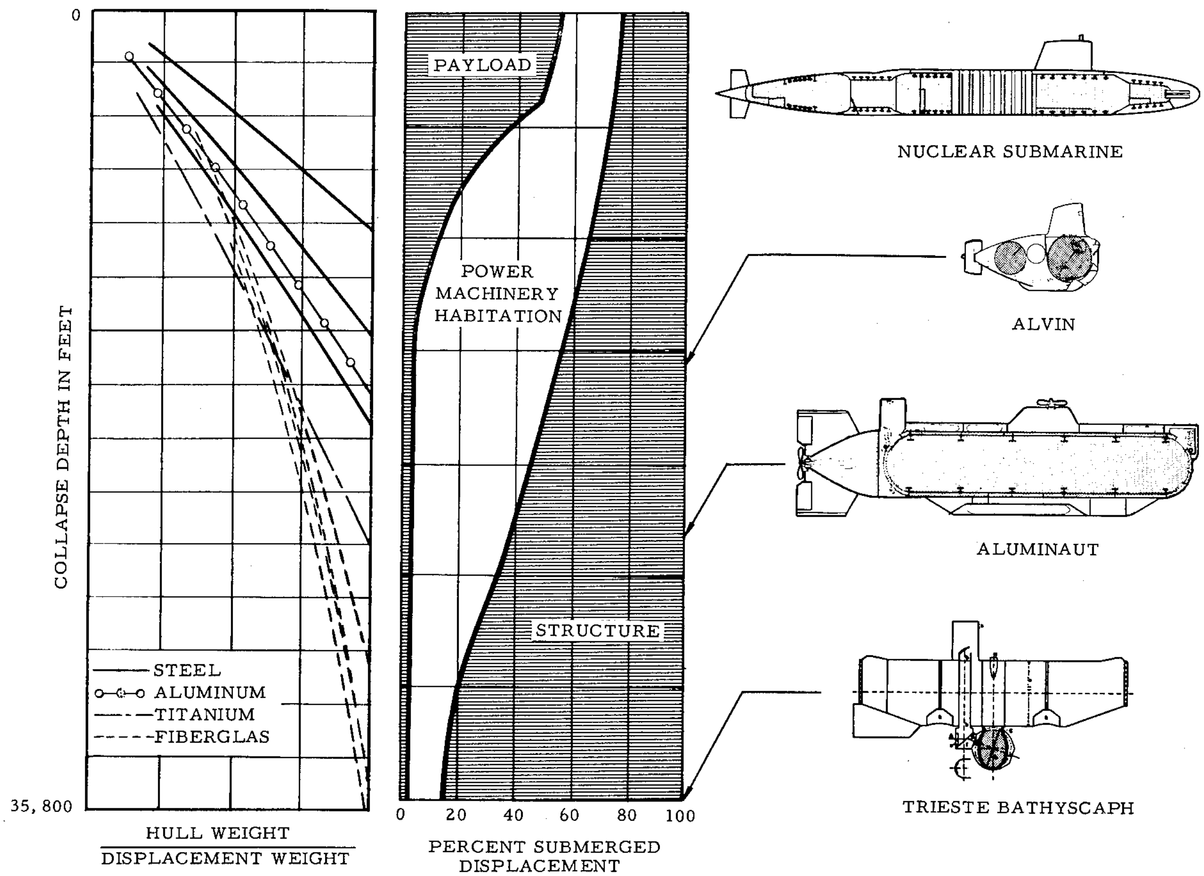


FIGURE IX-19.—Pressure-hull weight-efficiency comparisons for ring-stiffened cylindrical shells of various materials.

by the elastic compression of the hull, which decreases the displacement relative to water density and thus causes a deviation of neutral buoyancy with depth. The problem would be diminished by reducing the hull diameter or increasing the hull stiffness.

Alvin deep-submergence submarine.—This deep-submergence vehicle is required to carry a payload of 1,200 pounds to 6,000-ft. operating depths and to be operated by a crew of two in a spherical-shell pressure cabin of minimum 6½ ft. internal diameter, and of 1.25-in.-thick, HY 100 steel. Additionally, specific dimensions of Alvin, shown in figure IX–19, are 21 inches for the hatch diameter, 5 inches for the inside diameter of each of the four viewing ports, and 2 inches for the hatch viewing port. An 8-knot towing speed is also required and a 6-knot maximum speed in operation, with an endurance of twenty-four hours for a maximum range of thirty miles. Since the fineness ratio of a high-speed fleet ballistic-atomic submarine is not required, the vehicle has been developed around a spherical-shell pressure hull with a free-flooding, streamlined-shell, GFRP aft section. A major consideration in design is therefore the design of the spherical hull to achieve an operating depth of 6,000 feet with a safety factor of 1.8. Compared to short cylindrical steel shells with hemispherical ends, the spherical-shell concept achieves a weight saving of 15 percent. The use of GFRP filament-wound spherical-shell wall construction, or GFRP sandwich shell, could save even more weight, or, conversely, allow operation at greater depths for equal weight.

Aluminaut deep-submergence submarine.—The Aluminaut, figure IX–19, is a deep-submergence

research submarine, constructed as a cylindrically shaped pressure vessel for 15,000-ft. operating depths. The particular structural characteristics of this vehicle are an inside diameter of 84 inches, to provide reasonable headroom for a three-man crew, and a wall thickness of 6½ inches, of 7079–T6 aluminum material. This material is identified as the highest-strength aluminum alloy, 60,000-psi yield, in the large thicknesses required. The 36-hour endurance and 96-mile range of this vehicle, with 4.8 knots maximum speed, make it unique in its field. Since this proposed structures-research program is also centered on a 15,000-ft. operating depth, practical matters in design may be evaluated by further consideration of the Aluminaut characteristics. The vehicle has hemispherical-dome ends, which contain multiple viewing ports at the forward end and entrance hatches at each end. Thus, the cylindrical portion of the hull structure is not disturbed by large cutouts. This type of construction would have a practical parallel in filament-wound GFRP-hull concepts. Fatigue life is also a consideration in the Aluminaut, with an estimated 1,500 dives in 20 years, allocated as 500 to 5,000 feet, 500 to 10,000 feet, and 500 to 15,000 feet. The actual fatigue criterion used was 750 cycles to 15,000 feet, with a cycle factor-of-safety of 2 added. Model tests for this 7-ft.-diam. vehicle were initially conducted on 6-in.-diam. cylinders.

The pressure hull of this vehicle is so thick and stiff that it induces 500-lb. positive buoyancy at operating depths.

Trieste deep-submergence bathyscaph.—The Trieste deep-submergence bathyscaph is the most successful operating research vehicle of this type to date. The basic characteristics are shown in figure IX–19. The vehicle type is identified as a submerged free balloon. The buoyancy of the vehicle is provided by a cylindrical tank filled with sea-pressure-equalized gasoline. The pressure hull is essentially a spherical shell of 6-ft., 7-in. internal diameter. This shell was made as two hemispheres of more than 100,000-psi cast steel, which is machine-finished to contour. Also shown in the figure is a viewing port, which is integral with the hull, and a manhole-type hatch. The normal payload for this vehicle is limited to 500 pounds, which means that more than 80 percent of the vehicle weight is in its structure. Since the pressure sphere is relatively thick, the analysis of the sphere must consider thick shell properties. Buckling equations were not used by Piccard as a basis for design because of the thicknesses needed for a safety factor of 4.0 on 2½-mile-deep operation.

Fiber-glass boat.—The design conditions for boat hulls consist of longitudinal bending as a supported beam with wave loadings, hull-twisting loads, local water-pressure loads on panels, and equipment-installation loads. In some small boats, an unstiffened plywood shell with a protective fiber-glass skin has been quite popular. Usually the structure is frame-stiffened, then panel sections bounded by the frames experience water-pressure loadings. Attempts to use frame-stiffened GFRP skins with fiber-glass frames have met with limited success, because the flexural stiffness (EI) of the GFRP panel is less than that of plywood of equal weight. An alternate solution—using closer frame spacing—becomes more expensive. The best approach to solving local panel-design requirements is to use sandwich construction. Some of the core materials that have been considered are as follows:

(1) Wood
(2) Honeycomb
(3) Foams
(4) Woven, fluted GFRP cores
(5) Cubic, or egg-crate, GFRP material.

Plywood with GFRP facings is currently the most widely used core material and is typically found in the transoms of outboard motorboats, and as decks of larger boats. Balsa cores have been used also as deck materials, and some hardwoods have been contained in GFRP skins, but wood rot and, in the case of hardwoods, higher expansion coefficients crack the GFRP skins.

Honeycomb-core materials were introduced when fiber-glass construction was first used (fig. IX–20). Problems of water migration through the core cells of hull sandwiches and delamination of the skins from the core after impact damage have limited the use of this

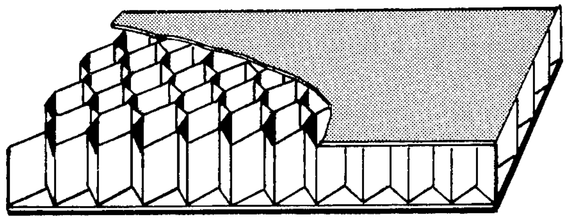


FIGURE IX–20.—Typical honeycomb-core structure.

stiff sandwich material to decks and superstructure.

Almost all resin systems may be compounded into foams. Successful applications consist of foaming-in-place a core between preformed polyester GFRP, contoured, and thickness-varying skins. This method of sandwich construction is most rapid, but processing problems, such as variations in core density and air pockets, are encountered. The density of foams approximates that of balsa, but the shear stiffness and strength are lower. Impact damage results in shear failure of the core. Variations in foam-core materials in the form of paste on microballoons have introduced a heavier, stronger core, which can provide local strengthening.

One of the most promising materials for boat hulls is the Raypan integrally-woven, fluted-core material (fig. IX–21) previously mentioned. This truss-core GFRP structure, with foam-filled cores, is buoyant and in comparison peel tests has a facing-to-core bond of 26.7 inch-pounds per inch, compared with 3.5 for fiberglass honeycomb core.

Another promising core material is constructed from chopped-fiber mat, in matched die molds. This type of construction has a checkerboard pattern of egg-crate-type arrangement, with alternating openings on one face through the other. A large increase in bond area is achieved in this core material, approaching 50 percent of the facings. The cells are individually sealed buoyant elements, which can withstand higher impact forces, as would be experienced on larger boat-construction applications.

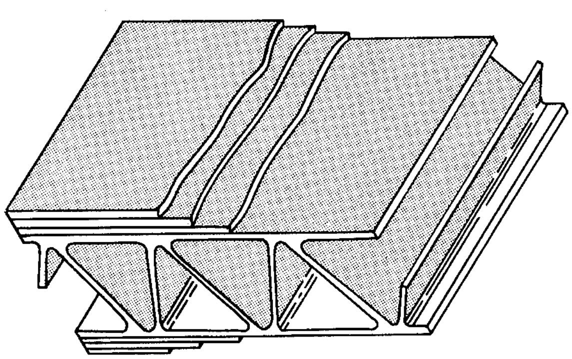


FIGURE IX–21.—Raypan truss-core GFRP structure.

Launch vehicles.—Spectacular successes have been achieved in solid-propellant booster-motor cases, particularly those of Polaris and Minuteman. These vehicle applications used filament-wound construction with improved-strength resin systems and glass filaments. Of equal importance to success were the improved tooling fabrication and quality-control techniques ensuring reliability in the completed cases. Proof pressures for the Minuteman cases were 587 psi, with ultimate pressure of 734 psi. The design concepts, which were first proven by Aerojet on the Polaris A–3 first- and second-stage rocket-motor cases, resulted in a composite allowable stress of 80,000 psi in the hoop direction at proof pressure. Corresponding design filament stresses at this proof pressure were 208,000 and 152,000 in the hoop and longitudinal filaments, respectively. The Minuteman cases were constructed of "E"–HTS filament-wound glass, and achieved the following strengths at burst pressure at a strain rate of 1 percent per minute:

Hoop composite strength	118,300 psi
Hoop filament strength	293,000 psi
Longitudinal filament strength	229,400 psi

The measured strength of S(994) HTS glass is 25 percent higher than that of "E"–HTS glass, and filament stress levels of 300,000 psi and 230,000 psi in the hoop and longitudinal directions, respectively, are anticipated at proof pressure.

Since weight is the basis for comparing rocket or launch-vehicle shell structures, a criterion has been developed for comparing monocoque filament-wound GFRP shells with sandwich shells. The break-even point occurs when the internal pressure and axial compression caused by flight loads are equally critical. When internal pressure is critical, as in the Polaris

case, monocoque is the more efficient concept. When compression is critical, shell-buckling sandwich configurations prove to be lighter. In studies conducted under Air Force contract by North American Aviation, a solid-propellant escape-vehicle case with 300-psi internal pressure for a defined mission proved to be lighter when using aluminum-core honeycomb with filament-wound GFRP facings.

Radomes.—The first extensive use of GFRP construction was in radomes. The first test demonstration of airborne radar equipment was in 1941. General indications were that the first radome was a ¼-inch-thick plywood hemisphere, which, since the operating microwave frequency was in the S-band (3 kilomegacycles), acted as a thin wall and hence did not require careful design. When, in 1942, service difficulties with plywood radomes due to moisture absorption were encountered, one solution was to add GFRP skins for protection, as in plywood boat construction today. By the end of 1942, when X-band (10 kilomegacycle) radars were used in B–24 bombers, severe radome-wall reflection was encountered for the all-GFRP, molded-polyester radomes. This problem emphasized the importance of keeping the single-wall radar thin with respect to the wavelength. The effort of evaluating this problem established rational procedures for electrical design of radomes. Wall thicknesses for radomes have since been limited to ½ wave dimensions, which introduces structural-strength problems in high-speed, high-pressure radome applications. A solution to this problem, which has now become a general concept of radome design, is the development of a double-wall, or sandwich-type, radome structure, with a limiting requirement of ¼-wavelength interval between walls. This sandwich form of construction resulted in the development of foamed cores, and in 1944 Wright Field developed honeycomb cores.

Current radome applications for subsonic aircraft include a means of heating the radome through fluted-core construction; hence, the development of Raypan GFRP material. Supersonic fighters have used single-wall, filament-wound, and ground radomes, and woven-fabric socks in laminate layups. The missiles proposed for hypersonic regimes have difficulty with GFRP materials when subjected to rain-erosion tests. Since rain erosion is a design consideration for radomes, ceramic monolithic and ceramic sandwich materials appear most promising. In large ground-radar systems, hemispherical radomes of over 100 feet in diameter have been configured, using GFRP honeycomb-core geodesic sandwich construction.

Rocket nozzles.—The liquid-propellant rocket motor makes use of regenerative cooling of the nozzle, by using either the liquid oxidizer or fuel as coolant. Solid-propellant rocket motors, on the other hand, may use the heat-sink principle, with materials such as graphite or tungsten. With increases in the size of these solid-propellant rockets, the weight and cost of fabrication may increase, with a deterioration of reliability. Reentry-vehicle nose-cone experience with ablative systems suggests this method of ablative cooling for rocket nozzles. One consequence of the use of ablative cooling is that the physical dimensions of the ablating material, particularly in the critical throat area of the nozzle, increase in size. Studies have related the effect of throat ablation on increase in diameter and chamber pressure, and now these nozzle types are a reality. Also borrowed from the nose-cone ablative-materials design concept is the winding of tape materials on specified orientations to prevent delamination. Hence, tape applicators are a requirement for the fabrication of rocket nozzles. Figure IX–22 shows the Northrop Ventura tape-wrapping applicator, which will accommodate parts up to 34 inches in diameter. The current development program is based on using phenolic-resin systems reinforced with carbon, graphite high silica, or asbestos tapes.

Airframe structures.—In the manufacture of more than 64,000 aerial targets, missiles, and logistics drones, the Northrop Corporation, Ventura Divison (formerly Radioplane), has always emphasized lightweight, low-cost, reliable airframes that can be easily repaired if damaged. These considerations have resulted in the extensive use of GFR plastics for primary airframe structure. Sufficient analytical and design technology has been developed in GFR plastics to assess properly the advantages

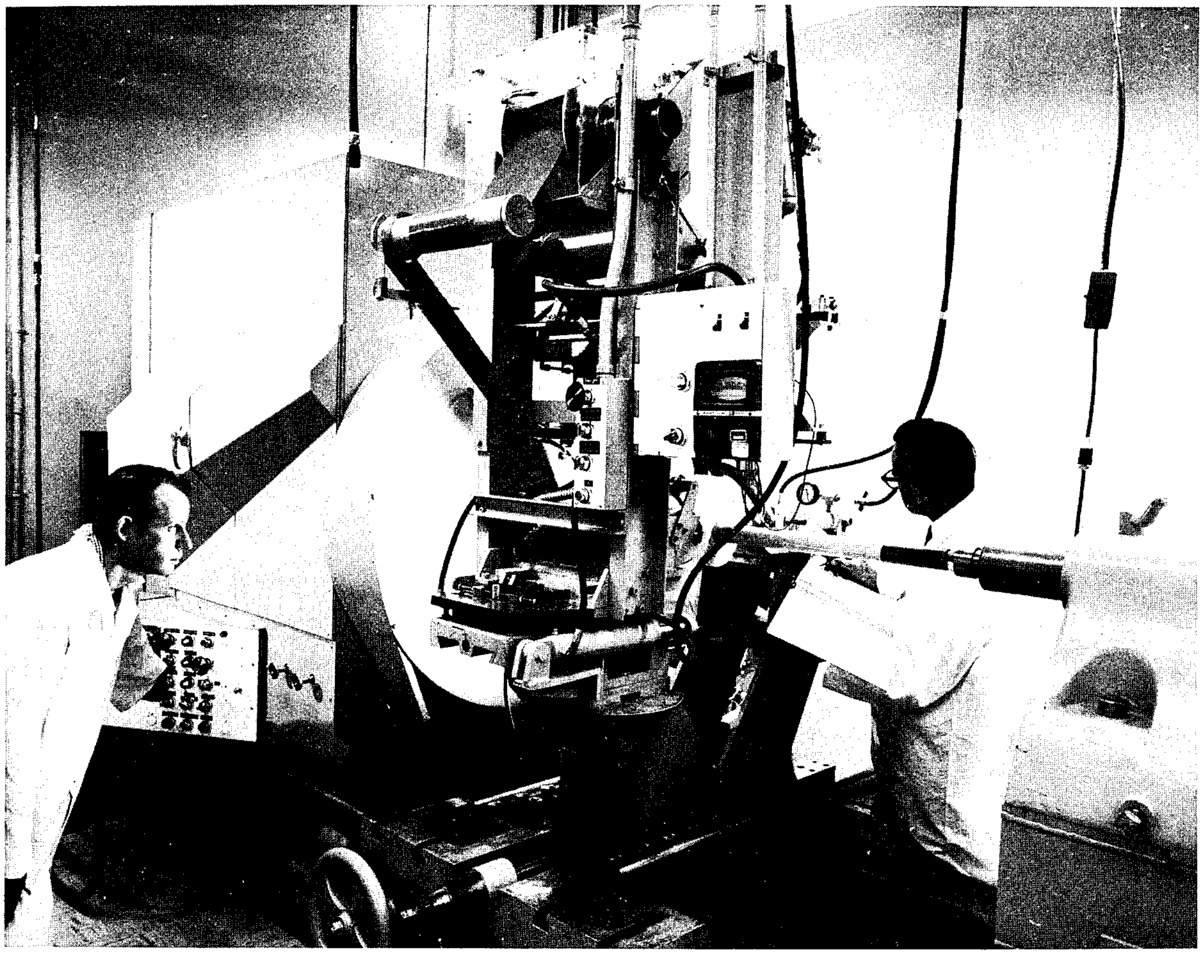


FIGURE IX–22.—Tape applicator for wrapping high-temperature plastic products.

and limitations of this material in primary airframe applications.

The RP–76 series of low-cost, rocket-powered, recoverable target drones is shown in figure IX–23. This is an air-launched target system, with later models capable of flight speeds up to Mach 3.2 and operating altitudes above 80,000 feet. Each member of this drone series is parachute-recovered.

The RP–76–3 is a high-altitude supersonic target for the Nike Hercules missile. Both the nose section and the aft fuselage are of GFR plastic-fabric laminate construction. The "T" tail arrangement established design requirements for maximum bending and torsional stiffness in the 181-fabric laminate shell. The extensive technology developed by the Ventura Division on directional layup of fabrics was employed to achieve the desired stiffness for minimum weight, which was substantiated by tests.

Figure IX–24 is an interior view of the plastics-molding facilities at Northrop Ventura, where RP–76 fuselages are made. This view shows series of matched-die-molding hydraulic presses, which have press platens heated by controlled liquid-heating systems. In the foreground is a Bliss hydraulic press of 300-ton-capacity. In figure IX–25, this press is shown after completing a matched-die molding operation on the 12-in.-diam. RP–76 rocket target's GFRP aft-fuselage section.

Another unmanned airframe, the RP–77 target drone, which has demonstrated the feasibility of using GFR plastic as primary structure, is shown with a Boeing turboprop powerplant in

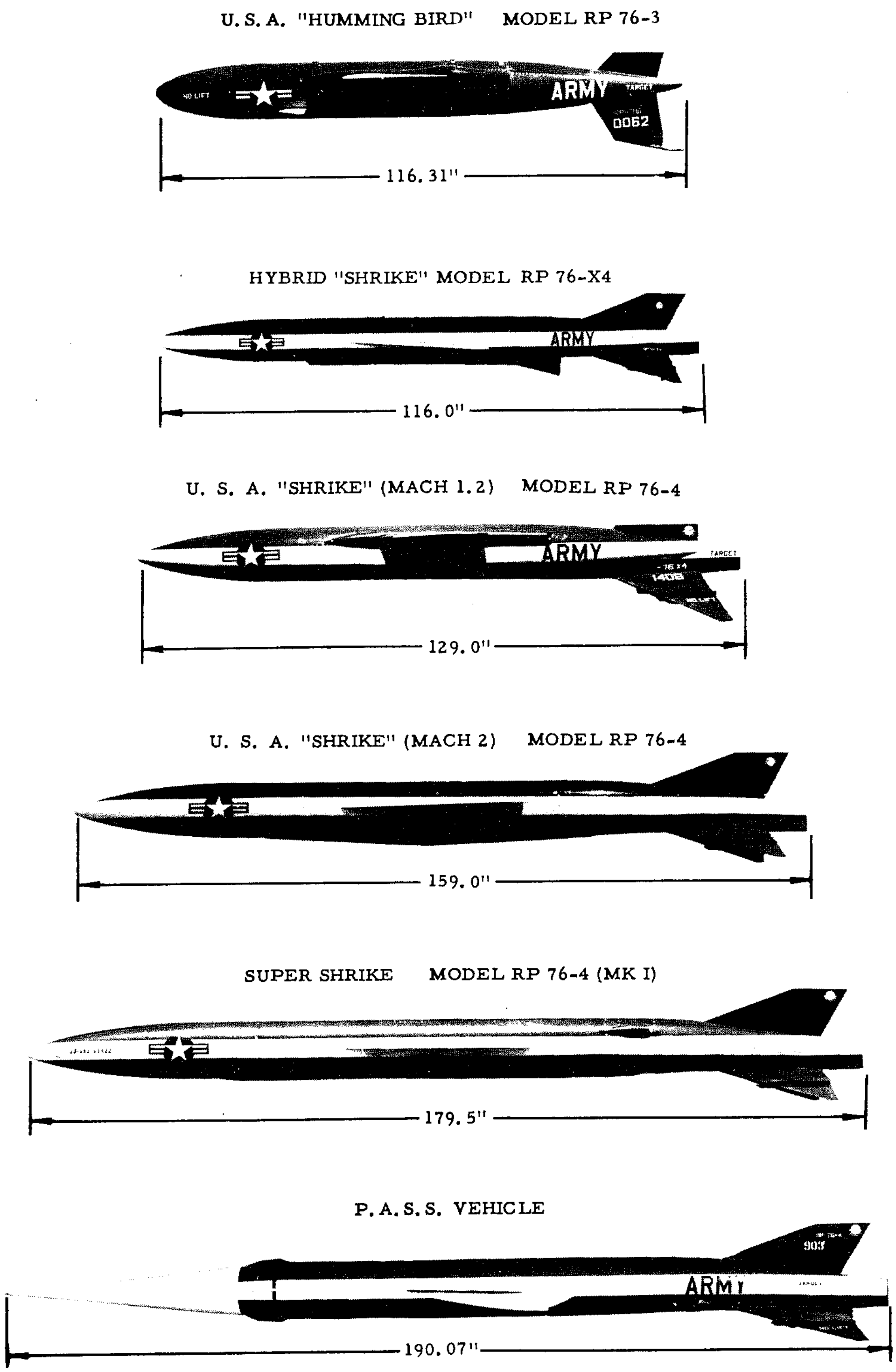


FIGURE IX-23.—The RP-76 series drones are maneuverable drone aerial vehicles for surface-to-air and air-to-air weapon-system test, training, and evaluation, as well as carriers for payloads.

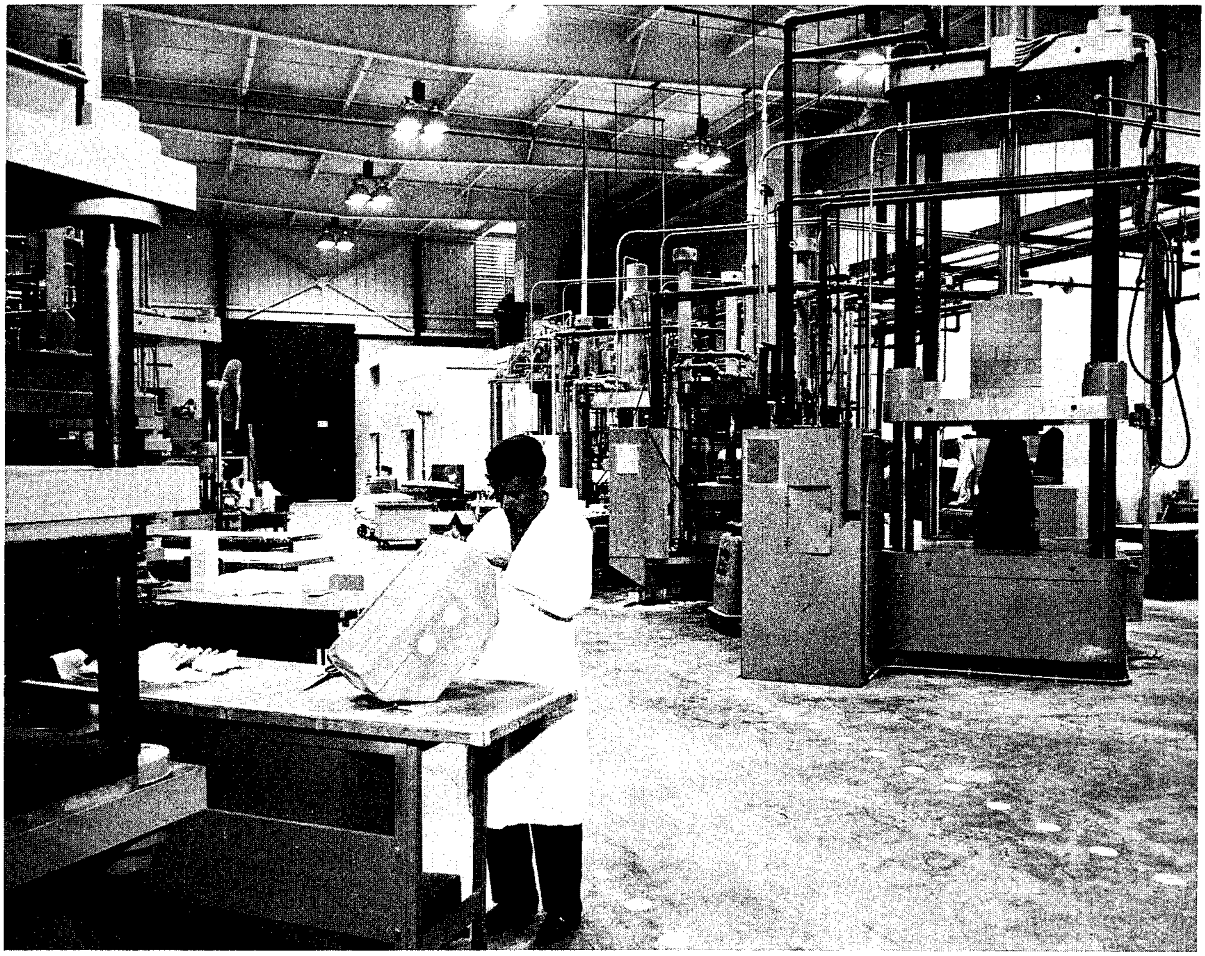


FIGURE IX-24.—Northrop Ventura plastics-molding shop.

figure IX–26. This drone has been repeatedly zero-length-launched and recovered by parachute to impact on its fuselage. The entire fuselage, including cowling, is constructed of 181-fabric layup with hat-section ring frames. Additional features of the RP–77 are foam-filled GFR-plastic wing leading- and trailing-edge structure.

A recent application of GFR plastic to a lightweight commercial aircraft is the British Beagle-Miles M–218. The design philosophy for this aircraft was to fill a gap between the lowest-powered, cheapest twin-engine airplane and the more costly and sophisticated single-engine types offered on the world's markets. The extensive use of GFR plastic was planned to produce an airframe rapidly and in quantity, at low cost in labor and material and without the need for complex or expensive tooling or specialized training operatives. The construction is of more than 60 percent GFR plastic, and consists of a basic airframe of a simplified but otherwise conventional metal wing box and fuselage beam structure, attaching to a GFR-plastic cabin, leading- and trailing-edge sections, and engine nacelles. Operational requirements for lightweight military aircraft of the COIN type emphasize a primitive environment in which aircraft can "live with the troops," require a minimum of maintenance manhours, and be readily repaired if damaged. Additional design requirements include 250-to-300 knots cruising speed, twin turboprop engines, and 8g maneuver-load factor. Preliminary con-

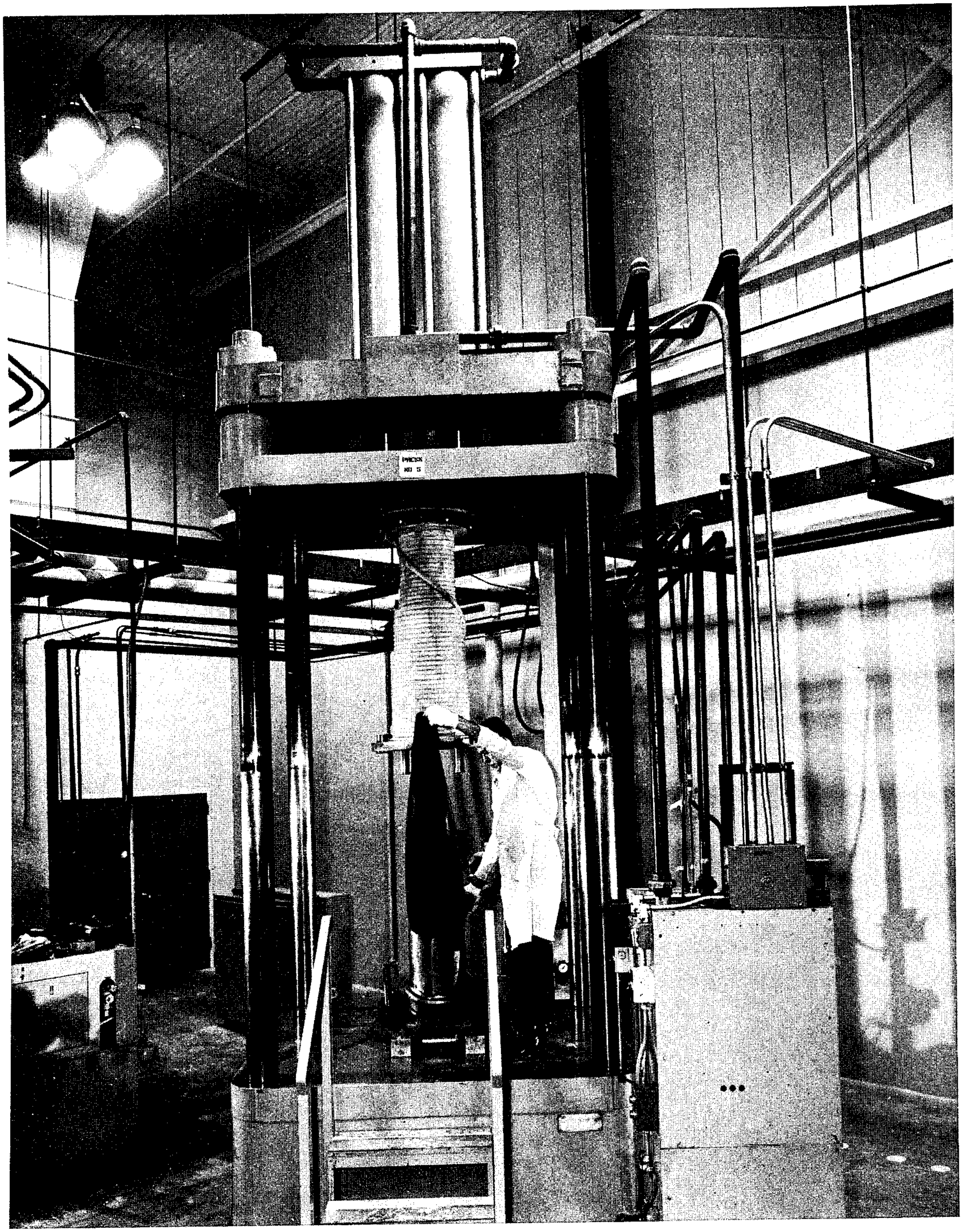


FIGURE IX–25.—Bliss 300-ton hydraulic press molding aft fuselage of RP–78 target drone.

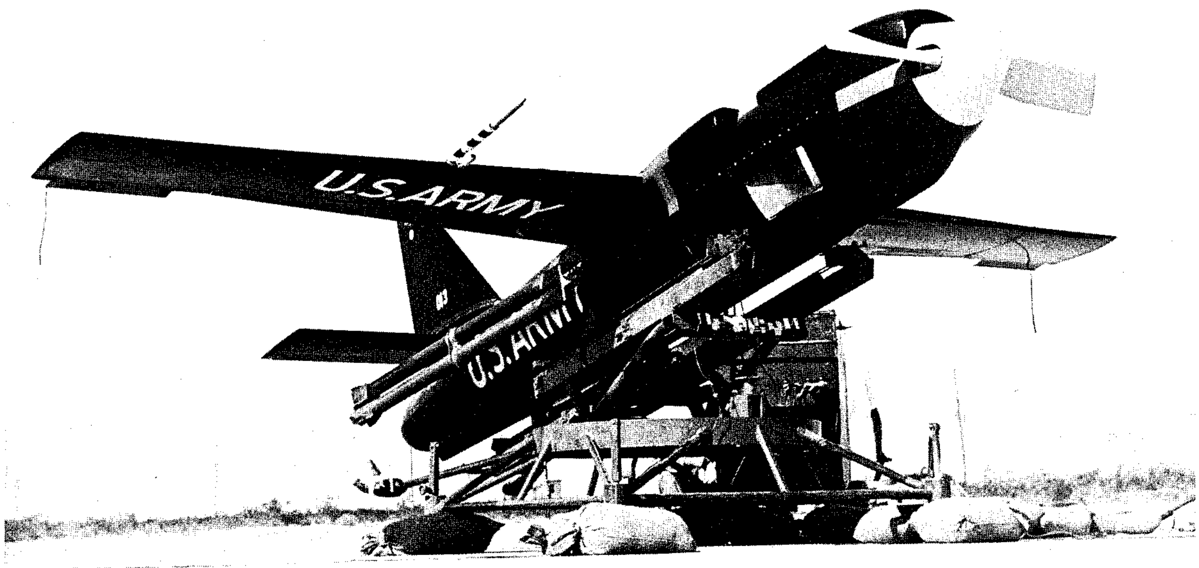


FIGURE IX-26.—RP-77 target drone, with all-plastic fuselage.

figuration studies that meet these requirements consider all-GFRP construction and include twin-boom arrangements, with a wing section sufficiently thick to meet wing-stiffness and minimum-weight requirements of GFR-plastic construction, using the new S(994) HTS glass.

DEVELOPMENT OF PRACTICAL WING-BOX STRUCTURE

The airframe designer is constantly balancing one design consideration against another to achieve an efficient but practical structure. The four major areas in which these compromises must be balanced may be considered as the symbols on his hypothetical coat-of-arms, as shown in figure IX-27.

The strength of the structure must be balanced by lightness to satisfy performance requirements, as has been discussed in the first part of this paper. The long-life, or fail-safe, features of the structure must balance strength, lightness, and cost. The strength, lightness, and fail-safe or structural-integrity aspects of

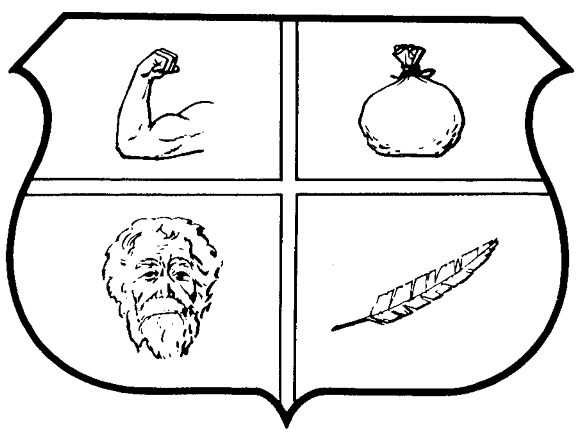


FIGURE IX-27.—Symbolic coat-of-arms of airframe designer.

MATERIAL COST	LABOR HOURS
$310.0	76.4
$293.0	84.4
$242.0	50.8

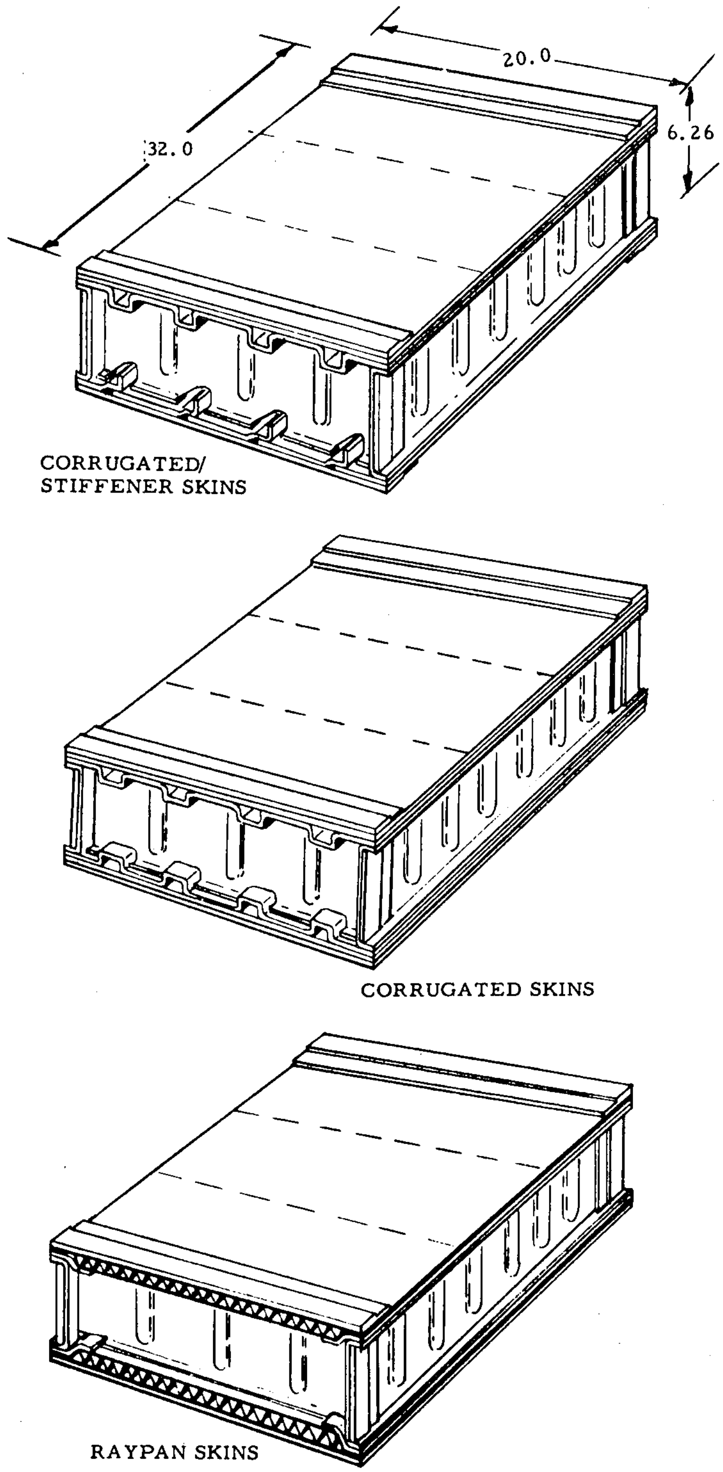


FIGURE IX-28.—Cost comparisons of three practical COIN-type wing-box structures constructed of S(994) HTS glass epoxy-GFR plastic.

the design concepts for S(994) glass in primary airframes structure have been considered. Therefore, in summary, three practical, experimental wing-box structures applicable to the COIN-type airframe are presented in figure IX–28, with comparisons on material costs and labor hours. These figures are based on S(994) glass, HTS finish, GFR plastic with an epoxy resin system. The lowest-cost structure is shown to be that which has been constructed of Raypan truss-core sandwich, which was also shown to be the most efficient compression panel (multi-spar) in figure IX–10. That figure also showed that the square corrugation is the lightest method of wide-column (multi-rib) wing-box panel construction. The most expensive box has a lower skin-tension panel, constructed for fail-safe design.

APPENDIX A

Deflection of Normally Loaded Panels

Consider that all edges of a panel are continuously supported and that the panel is loaded by a distributed normal load of intensity q. The equations of static equilibrium on element dy, dx are (see fig. IX–29)

$$\frac{\partial^2 M_x}{\partial x^2}+\frac{\partial^2 M_{yx}}{\partial x \partial y}+\frac{\partial^2 M_y}{\partial y^2}-\frac{\partial^2 Mxy}{\partial x \partial y}=-q$$

considering $M_{yx}=-M_{xy}$

then

$$\frac{\partial^2 M_x}{\partial x^2}-\frac{2\partial^2 M_{xy}}{\partial x \partial y}+\frac{\partial^2 M_y}{\partial y^2}=-q \qquad \text{(A–1)}$$

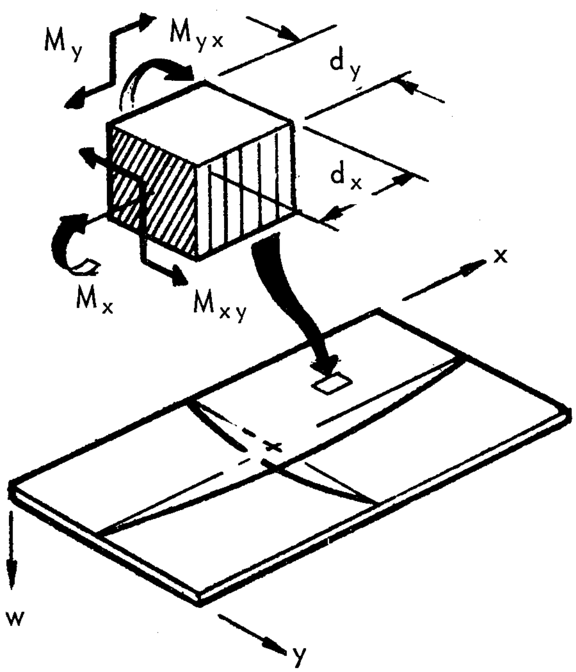


FIGURE IX–29.

From elementary beam theory

$$\left(\frac{M}{EI}\right)_x=\frac{d^2 w}{dx^2}$$

The moment M_x on one face of an element of a panel induces a moment due to Poisson's ratio effects, thus:

$$M_x=\frac{(E\bar{I})_x}{(1-\mu_x\mu_y)}\left(\frac{\partial^2 w}{\partial x^2}+\mu_y\frac{\partial^2 w}{\partial y^2}\right)$$

moment/unit width (A–2)

$$M_y=-\frac{(E\bar{I})_y}{(1-\mu_x\mu_y)}\left(\frac{\partial^2 w}{\partial y^2}+\mu_x\frac{\partial^2 w}{\partial x^2}\right)$$

moment/unit length (A–3)

$$M_{xy}=2(G\bar{I})_{xy}\frac{\partial^2 w}{\partial x \partial y}$$

unit twisting moment (A–4)

let

$$D_x=\frac{(E\bar{I})_x}{(1-\mu_x\mu_y)}$$

longitudinal bending stiffness/unit width (A–5)

$$D_y=\frac{(E\bar{I})_y}{(1-\mu_x\mu_y)}$$

transverse bending stiffness/unit length (A–6)

$$D_{xy}=\frac{1}{2}\left(\mu_x D_y+\mu_y D_x\right)+2(G\bar{I})_{xy}$$

unit twisting stiffness (A–7)

Differentiating equations A–2, A–3, and A–4, and substituting the stiffness symbols D_x, D_y

and D_{xy}, then:

$$\frac{\partial^2 M_x}{\partial x^2}=D_x\left(\frac{\partial^4 w}{\partial x^4}+\mu_y\frac{\partial^4 w}{\partial x^2\partial y^2}\right. \qquad \text{(A–8)}$$

$$\frac{\partial^2 M_y}{\partial y^2}=D_y\left(\frac{\partial^4 w}{\partial y^4}+\mu_x\frac{\partial^4 w}{\partial x^2\partial y^2}\right) \qquad \text{(A–9)}$$

$$\frac{\partial^2 M_{xy}}{\partial y^2}=2(G\bar{I})_{xy}\frac{\partial^4 w}{\partial x^2\partial y^2} \qquad \text{(A–10)}$$

Substituting A–8, A–9, and A–10 in A–1, and grouping similar terms such as

$$\frac{\partial^4 w}{\partial x^2\partial y^2},$$

the deflection equation for an element of panel loaded by a distributed normal load of intensity q is

$$q=D_x\frac{\partial^4 w}{\partial x^4}+2D_{xy}\frac{\partial^4 w}{\partial x^2\partial y^2}+D_y\frac{\partial^4 w}{\partial y^4} \qquad \text{(A–11)}$$

Deflection of Axially Loaded Panels

In the case of uniform compression-loading of a panel parallel to the X axis of magnitude N_x/unit width, a lateral buckling deflection may be induced that can be expressed by equation A–11 with q replaced by $N_x\frac{\partial^2 w}{dx^2}$ (see fig. IX–30), as follows:

$$N_x\frac{\partial^2 w}{\partial x^2}=D_x\frac{\partial^4 w}{\partial x^4}+2D_{xy}\frac{\partial^4 w}{\partial x^2\partial y^2}+D_y\frac{\partial^4 w}{\partial y^4} \qquad \text{(A–12)}$$

Assuming that the deflected shape consists of a series of half-sine waves (m) in the X direction and (n) in the Y direction (see fig. IX–31) expressed by the equation

$$w=w_o\sin m\,\pi\frac{x}{a}\sin n\,\pi\frac{y}{b} \qquad \text{(A–13)}$$

Taking successive derivatives of the sine-wave equation (w) gives

$$\frac{\partial^2 w}{\partial x^2}=\left(\frac{m\pi}{a}\right)^2\left\{w_0\sin m\pi\frac{x}{a}\sin n\pi\frac{y}{b}\right\}$$

$$\frac{\partial^4 w}{\partial x^4}=\left(\frac{m\pi}{b}\right)^4\left\{w_0\sin m\pi\frac{x}{a}\sin n\pi\frac{y}{b}\right\}$$

$$\frac{\partial^4 w}{\partial y^4}=\left(\frac{n\pi}{b}\right)^4\left\{w_0\sin m\pi\frac{x}{a}\sin n\pi\frac{y}{b}\right\}$$

$$\frac{\partial^4 w}{\partial x^2\partial y^2}=\left(\frac{m\pi}{a}\right)^2\left(\frac{n\pi}{a}\right)^2\left\{w_0\sin m\pi\frac{x}{a}\sin n\pi\frac{y}{b}\right\}$$

Substitute the above derivations in equation A–12 with the common terms in the large brackets eliminated, then:

$$N_{x_{cr}}\left(\frac{m\pi}{a}\right)^2=D_x\left(\frac{m\pi}{a}\right)^4+2D_{xy}\left(\frac{m\pi}{a}\right)^2\left(\frac{n\pi}{b}\right)^2+D_y\left(\frac{n\pi}{b}\right)^4 \qquad \text{(A–13)}$$

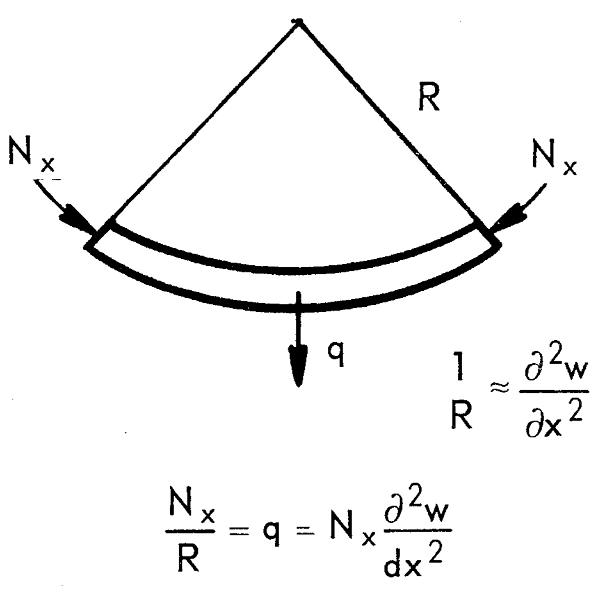


FIGURE IX–30.

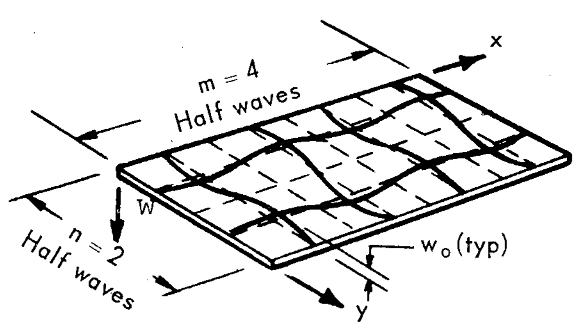


FIGURE IX–31.

consider the buckle pattern is $n=1$ half wave in the transverse direction and reducing equation A–13.

$$N_{x_{cr}}=\frac{\pi^2}{b^2}\left[D_x\left(\frac{m}{a/b}\right)^2+2D_{xy}+D_y\left(\frac{a/b}{m}\right)^2\right] \quad \text{(A–14)}$$

reducing A–14 further

$$N_{x_{cr}}=\frac{\pi^2}{b^2}D_x\sqrt{\frac{D_y}{D_x}}$$
$$\left[\left\{\frac{m}{\frac{a}{b}\sqrt[4]{\frac{D_y}{D_x}}}\right\}^2+2\frac{D_{xy}}{D_x}\sqrt{\frac{D_x}{D_y}}+\left\{\frac{\frac{a}{b}\sqrt[4]{\frac{D_y}{D_x}}}{m}\right\}^2\right] \quad \text{(A–15)}$$

By differentiation of (A–15) a minimum buckling solution occurs when

$$m=\frac{a}{b}\sqrt[4]{\frac{D_y}{D_x}} \quad \text{(A–16)}$$

substituting A–16 in A–15

$$N_{x_{cr}}=\frac{2\pi^2}{b^2}D_x\sqrt{\frac{D_y}{D_x}}\left[1+\frac{D_{xy}}{D_x}\sqrt{\frac{D_x}{D_y}}\right]$$
$$=\frac{2\pi^2}{b^2}D_x\sqrt{\frac{D_y}{D_x}}(1+k_G)\text{ lb/in.} \quad \text{(A–17)}$$

where considering equation A–7 and A–17,

$$k_G=\frac{D_{xy}}{D_x}\sqrt{\frac{D_x}{D_y}}=\frac{\frac{1}{2}(\mu_xD_y+\mu_yD_x)+2(GI)_{xy}}{D_x\sqrt{D_y/D_x}} \quad \text{(A–18)}$$

considering $\mu_xD_y=\mu_yD_x$, then

$$k_G=\frac{\mu_y+2(G\overline{I})_{xy}/D_x}{\sqrt{D_y/D_x}} \quad \text{(A–19)}$$

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X. Advanced Computer Applications

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Participants in this symposium have been asked to base their remarks on research-and-development activities being conducted within their own organizations. I have chosen four such activities as examples, having to do with applications of high-speed digital computers. The projects are related to the space program in that they deal with problems to be found in that program, but in the same sense they are also related to defense and other programs. Indeed, to assure their widest applicability, the projects are being conducted at a level removed as much as possible from the particular requirements of any specific user.

Research and development concerned with computer applications deal in part with the end use to be made of a computer system and in part with the means for achieving such use. Although the distinction is somewhat arbitrary, most efforts can be identified as concentrating primarily on one or the other. With respect to the computer-programing involved, the difference is largely that between applied and system programing. With respect to the major goals pursued, however, the difference is better expressed by the self-explaining labels "What?" and "How?"

Those most actively concerned with research and development of "What?" type are typically specialists in another field. They regard the computer and its programs as a resource to be combined with other resources in the attempt to solve problems. The problems may even be defined without reference to a computer, although a computer is required for their solution.

Expanding the resource potential of the computer is the goal of "How?" research and development. The end products of this activity—when any result—are made available as raw materials for those dealing with "What?"

It is interesting to note that access to a computer is necessary, although not sufficient, for those who deal with the computer and its programs as an incidental tool. On the other hand, a computer is not even necessary for much of the "How?" work, in which many of the problems can be attacked at the level of pure theory.

EDUCATION AND TRAINING

One of the groups at System Development Corp. concerned with research and development in education and training has eight professional members, of whom only one is a programer. No more information is needed to decide that this group does "What?" research. That their work depends intimately upon a computer, however, is indicated by the name of the facility in which most of it is done—the Computer-Based Laboratory for Automated School Systems. (Initial letters of the name reflect the well-known tendency of programers to select meaningful acronyms.)

Developing instructional systems that provide optimum conditions for effective learning is one of the project goals. Programed instruction administered through a computer furnishes a basic vehicle for this work. The term "programed instruction" is in general use to describe any method for sequential presentation of learning materials organized to permit progressive mastery of items covering small units of information. In the CLASS facility, the presenta-

tion sequence for any number of individual students from one to twenty is under computer control. Either visual or auditory presentation modes are available, and the student, in responding to a question item, communicates with the computer by pressing an appropriate button.

Alternatives in the presentation sequence are possible with one form of programed instruction, the branching program. The lesson is organized into a main stream, in which a few items cover the whole topic to be mastered, and a number of remedial sequences providing smaller steps between main-stream items. By using a computer to administer a branching program, the sequence of items presented to an individual learner may be placed under the simultaneous control of several parameters. In particular, branching into a remedial sequence may be caused by a specific wrong answer, by a cumulative score that drops below a present criterion level, or by a student response on a self-evaluation item.

Some of the work on computer-based instruction is of course concerned with the development of appropriate lesson materials. These materials, like the computer programs, are of secondary interest, however. The major problem is to use all the resources available to investigate and capitalize on the interactions of task, method, and subject variables.

Computer-based instruction may find a number of uses in the near future to carry out courses of specialized training. However, the time has not yet arrived for its widespread utilization as part of the general education process. The cost of a computer, associated equipment, and instructional materials would represent a major investment even if all were available. There are additional costs—not all measurable in dollars—in integrating this method with existing systems of instruction and administration. A great deal of research remains to be done in identifying the important variables, in improving techniques of constructing effective learning materials, and in determining the best means of employing the method. But some of this research must be done before it can be decided whether the payoff will exceed the financial and social cost.

QUESTION-ANSWERING

Another group of studies illustrating "What?" research and development falls under the heading "Artificial Intelligence." That polysyllabic designation refers to attempts to provide machines with the ability to act in ways that are called intelligent when people act in similar ways under similar circumstances. One of the projects in this area has been to devise a computer system with the ability to use an open-ended collection of English text to answer questions asked in ordinary English. Several versions have been implemented, the most recent using a teletype both to ask the questions and to receive the answers.

New text enters the system through the medium of punched cards. A word is recognized as a string of alphabetic characters bounded by blanks or punctuation marks. The words are stored sequentially on magnetic tape for use in later processing, and if the word being processed is a content word, the tape location is noted in a cumulative index arranged according to grammatical root forms. A word is automatically classed as a content word if it does not appear in a list of some 300 function words. Entries in the function-word list include articles, conjunctions, prepositions, and the other most common words of English that establish the structure of a sentence but carry little meaning in themselves.

When a question is entered in the machine, the computer first identifies all the content words, then uses the index to determine paragraphs or sentences of the text that include those content words or their variants. The potential answers selected in this fashion are scored for relevance to the question, taking into account the number of content words common to both the question and the potential answer. The scoring algorithm considers the frequency with which any content word appears in the whole text, giving greatest weight to words that occur least often. Any sentence or paragraph whose relevance score exceeds a minimum value is finally retrieved from the tape and printed as an answer to the question.

The question-answering system has been designed to deal with text where it is difficult or

impossible to anticipate in advance the nature of questions that will be asked. Such a situation arises in conducting a literature survey, and a feasibility study is being conducted to determine whether the system can serve the Science Information Exchange in retrieving document abstracts. Another study, in collaboration with the Los Angeles Police Department, is investigating the possibilities of using the system to retrieve crime-report data.

TIME-SHARING

An example of "How?" research and development is the construction of a system that allows many users simultaneous access to a computer. The various users may be performing calculations or interrogating data files. They may be serving as subjects in a research project. They may be compiling or debugging computer programs. They may even be writing new programs one instruction at a time, and observing the effect as each is executed. All these operations may be going on at the same time, each individual user behaving as if he had the computer and its programs all to himself.

The system is possible because the computer operates so much faster than the human user. Within each cycle, the total computing time is shared among the individual users, each receiving service in turn. A significant amount of computing time can be devoted to each user within a program cycle lasting only a few seconds. To the individual user, the system appears to be in continuous use by himself alone.

Appearance to the executive program is something else. Individual user programs in their current states are shuffled back and forth between high-speed storage and magnetic drums as necessary. Time allocations are computed dynamically according to the number of active user programs, their size, and their input-output requirements. Input and output requests are performed on demand, and auxiliary storage media are assigned as needed. An on-line interpreter permits immediate execution of commands expressed in the language of the time-sharing system, and an on-line debugger gives a programer access to the contents of his program.

Communication between the time-sharing computer and the user is accomplished by teletypes or display consoles. Teletype connections have been set up with East Coast locations on several occasions, and a number of remote users have continuous access to the system via computer-to-computer link or teletype. One of these is the Los Angeles Police Department, using a teletype in connection with the crime-report-retrieval study mentioned earlier. Another is a Veterans' Administration hospital, participating in a study on patient-data automation.

COMMON PROGRAMING SUPPORT SYSTEM

A final example provides another instance of "How?" development. The Common Programing Support System has been designed for use by programers in constructing program systems. Computer programs are almost invariably put together with the assistance of other programs. Perhaps the best-known example is the compiler, which produces an operating program from statements written in a symbolic programing language. A number of additional support programs are also usually employed when a system of interrelated programs is to be produced. Their function is to provide for the integration and testing of the programs that make up the operational system. Collectively, they make up a utility system or support system.

A variety of support systems has been produced for use with different computers and for the construction of different operational systems. Although these support systems vary considerably in their design, the basic functions performed are almost identical. Hence, the effort to develop a Common Programing Support System with a high degree of transferability from machine to machine or application to application.

Motivation for the effort has been to reduce the time and cost of providing reliable operational systems for Federal Government programs. The system is independent of the particular end use, however, so that it may be applied equally well in non-government use.

DISCUSSION

The four projects I have described were presented as examples of research and development in digital-computer applications that have some potential for use in the general economy. It is important to recognize that they are only examples. They neither present a balanced picture of the total research-and-development effort at SDC nor indicate the extent to which comparable efforts are being pursued elsewhere. The total impact on the general economy will come as many groups explore the many aspects of the broad problem areas described.

Both the "How?" efforts and the "What?" efforts have played important parts in the past development of advanced computer applications, and both must be encouraged for progress in the future. The distinction between them, like that between means and ends, serves to focus attention on two complementary processes. Different kinds of people tend to be involved, and the immediate goals are not at all the same. Neither type of effort makes sense, however, unless it is considered in relation to the other.

No discussion of advanced computer applications is complete unless it also considers a third type of research-and-development effort—that concerned with machines as machines. Dramatic improvements have been made in computers and associated equipment over the past few years. There is every reason to believe that more will be made in the future. Perhaps there is even reason to hope that the physical problems of communication between man and machine will be resolved. Certainly the full possibilities in some of the projects described earlier cannot be realized completely without this and other advances in the physical equipment. I have not talked about these possibilities, for there is no research of that nature going on at SDC, but real advancement in the application of computers will only occur when both "What?" research and "How?" research can be correlated with research in this third important field.

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